**O‘zR FA FIZIKA-TEXNIKA INSTITUTI
HUZURIDAGI ILMIY DARAJALAR BERUVCHI
DSc.02/27.02.2020.FM/T.110.01 RAQAMLI ILMIY KENGASH**

FIZIKA – TEXNIKA INSTITUTI

MAVLONOV ABDURASHID ABDUVAHOBOVICH

$Cu(In,Ga)Se_2$ VA Sb_2Se_3 ASOSIDAGI YUPQA QATLAMLI QUYOSH ELEMENTLARINI TAYYORLASH VA FIZIK XOSSALARINI O‘RGANISH

**01.04.10 – Yarimo‘tkazgichlar fizikasi
(fizika-matematika fanlari)**

**E’LON QILINGAN ILMIY ISHLAR BO‘YICHA DISSERTATSIYASIZ
FAN DOKTORI (DSc) ILMIY DARAJASINI OLISH UCHUN
TAQDIMNOMA**

Toshkent – 2024

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Fizika-matematika fanlari doktori (DSc) taqdimnomasi mundarijasi

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Taqdimnoma mavzusi O‘zbekiston Respublikasi Oliy ta’lim, fan va innovatsiyalar vazirligi huzuridagi Oliy attestatsiya komissiyasida B2023.4.DSc/FM249 raqami bilan ro‘yxatga olingan.

Taqdimnoma O‘z.Res. Fanlar Akademiyasi Fizika Texnika Institutida bajarilgan.

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Taqdimnoma himoyasi O‘z.Res. Fanlar akademiyasi Fizika-texnika instituti huzuridagi DSc.02/27.02.2020.FM/T.110.01 raqamli Ilmiy kengashning 2024-yil 22-avgust soat 10^{00} dagi majlisida bo‘lib o‘tadi. (Manzil: 100084, Toshkent shahri, Chingiz Aytmatov ko‘chasi, 2B, Fizika-texnika instituti, katta majlislar zali; tel.: 71 235-42-91.; e-mail: ftikans@uzsci.net).

Taqdimnoma bilan Fizika-texnika institutidagi Axborot-resurs markazida tanishish mumkin (381-raqami bilan ro‘yxatga olingan). (Manzil: 100084, Toshkent shahri, Chingiz Aytmatov ko‘chasi 2B, Fizika-texnika instituti kutubxona; tel.: 71 235-42-91)

Taqdimnoma 2024-yil “____ ” ____________ kuni tarqatildi.

(2024-yil “___” __________ dagi № ____ raqamli reestr bayonnomasi).

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KIRISH (fan doktori (DSc) taqdimnoma annotatsiyasi)

Mavzuning dolzarbligi. Dunyoda ekologik toza va qayta tiklanuvchi energiya manbalarini hozirgi kundagi yoqilgi- energiya resurslari (neft, tabiiy gaz, koʻmir) oʻrniga muqobil sifatida rivojlantirish soha olimlari oldidagi eng muhim vazifalardan biriga aylangan. Ushbu sa’y-harakatlar, yani neft, koʻmir va tabiiy gazni ommaviy iste’mol qilishni kamaytirish orqali Yerdagi biotizimlarni himoya qilishga asoslangan. Amalda, mavjud energiya resurslarini yangi turdagi muqobiliga almashtirish bosqichma-bosqich amalga oshirilib kelmoqda. Shu nuqtai nazardan, energiya resurslaridan foydalanish tahlili “21-asr energiya strukturasi”ni turli qayta tiklanadigan energiya shakllarini oʻz ichiga olgan “Eng yaxshi muvofiqlik davri” sifatida tavsiflanishini nazarda tutadi. Ekologik toza energiya ishlab chiqarish texnologiyalarini rivojlantirish loyihalari orasida fotovoltaik texnologiyalar, ya’ni quyosh elementlari (QE) asosida quyosh nuridan bevosita elektr energiyasi olish, eng istiqbollilaridan biriga aylandi. Bu texnologiya shovqinsiz, tutun kabi ifloslanishsiz insoniyatga beminnat elektr energiyasi ishlab chiqarish imkonini beradi. Quyosh elementlarining oʻlchamini tanlash orqali bu texnologiya millivatt (mW) dan megavatt (MW) oraligʻida elektr energiyasini ishlab chiqarish imkonini beradi.

Jahonda dastlabki davrda (1950-70 yillar), quyosh elementlarini amaliy qoʻllanishi faqat kosmos loyihalarida, yerning sun’iy yoʻldoshlarini elektr energiyasi bilan taminlash uchun ishlatilishi bilan chegaralangan boʻlsada (bunga sabab quyosh elementlari tannarxi hozirgi kundagilaridan bir necha ming barobar qimmat boʻlgan), ushbu dastlabki davrdagi sohaga qaratilgan etibor hozirgi kundagi erishilayotgan yutuqlarga poydevor vazifasini oʻtab kelmoqda. Hozirda quyosh elementlarini turli geografik makonlarda, choʻllar, bino tomlari va tashqi yuzasi, transport vositalari va hattoki koʻl va dengiz yuzlarida (“floating PV”) koʻrishimiz mumkin. Uzliksiz olib borilayotgan ilmiy tadqiqotlar natijasida quyosh elementlarini samaradorligi ortib, ishlab chiqarish koʻlami kundan-kunga ortib bormoqda. Biroq, Quyosh modullarining tan narxini yanada arzonlashtirish hozirgi kundagi eng ustuvor vazifalardan biri hisoblanadi. Ushbu jabhada soʻnggi oʻn yillikda quyosh elementlari uchun kerakli xom-ashyo materiallaridan sanoat darajasida ishlab chiqarish jarayonlarigacha, barcha texnik bosqichlarda keng koʻlamli tadqiqot va izlanishlar olib borilmoqda. Binobarin, fotovoltaik texnologiyalarning narxi sezilarli darajada pasaygan, natijada quyosh stansiyalaridan olinayotgan elektr energiyasining narxi hozirgi yoqilgi- energiya resurslaridan ishlab chiqarilayotgan energiya tannarxiga yaqinlashmoqda. Ushbu texnologiyani yanada raqobatbardosh qilish uchun harajatlarni yanada pasaytirish kerak. Hozirgi kunda polikristall va monokristall kremniy asosidagi quyosh panellari quyosh energiyasi bozori ulushining asosiy >90% qismini tashkil etadi, qolgan <10% esa CdTe va Cu(In,Ga)Se_2 (CIGS) kabi yangi turdagi yupqa qatlamli quyosh panellariga toʻgʻri keladi. Ushbu quyosh elementlarning samaradorligi laboratoriya miqyosida >22% ga va modul darajasida 20% ga yaqinlashgan. Bu koʻrsatkichlar bitta p-n oʻtishli quyosh elementlari uchun olingan. Harajatlarni yanada pasaytirish uchun bir qancha ilmiy muammolarga yechim topish zarur. Fotovoltaik texnologiyalarga asoslangan ikki va undan ortiq p-n oʻtishli quyosh elementlarini (Tandem quyosh elementlari) ishlab chiqarish yoki yer yuzida keng tarqalgan, arzon kimyoviy elementlar asosida samarali quyosh elementlarini tadqiq qilish va ishlab chiqish istiqbolli dolzarb vazifalardan hisoblanadi.

Respublikamizda keyingi yillarda ilm-fan va texnologiyalarni dolzarb va ustuvor yo‘nalishlarini rivojlantirish uchun fundamental va amaliy tadqiqotlarga tobora ko‘proq e’tibor qaratilmoqda. Xususan, istiqbolli yo‘nalishlardan biri bo‘lgan nazariy va amaliy fizik tadqiqotlarni rivojlantirish bugungi kunning muhim masalasidir. Mamlakatimizda ilm-fanni muvaffaqiyatli rivojlantirish bo‘yicha fundamental tadqiqot va ishlanmalarning asosiy yo‘nalishlari va ularni amaliyotda qo‘llash 2022-2026-yillarda O‘zbekiston Respublikasini yanada rivojlantirish bo‘yicha Strategiyasida o‘z ifodasini topgan. Shuning uchun yuqori samaradorlikka ega quyosh elementlarini o‘rganish fundamental va amaliy tadqiqotlar sohasidagi dolzarb masalalardan biri bo‘lib qolmoqda.

Mazkur ilmiy tadqiqot ishi quyidagi davlat me’yoriy hujjatlari bilan belgilangan vazifalarga mos keladi: O‘zbekiston Respublikasi Prezidentining 2017-yil 07-fevraldagi “O‘zbekiston Respublikasini yanada rivojlantirish bo‘yicha harakatlar strategiyasi to‘g‘risida”gi PF-4947-son Farmoni, O‘zbekiston Respublikasi Prezidentining 2017-yil 18-fevraldagi “Fanlar akademiyasi faoliyatini yanada takomillashtirish, ilmiy-tadqiqot faoliyatini tashkil etish, boshqarish va moliyalashtirish chora-tadbirlari to‘g‘risida”gi PQ-2789-son qarori va boshqalar.

Tadqiqotning O‘zbekiston Respublikasining fan va texnikasini rivojlantirishning asosiy ustuvor yo‘nalishlariga muvofiqligi. Mazkur dissertatsiya tadqiqotlari O‘zbekiston respublika fan va texnologiyalar rivojlanishining II. “Energiya va resurslarni tejash” ustuvor yo‘nalishiga muvofiq bajarilgan.

Taqdimnoma mavzusi bo‘yicha xorijiy ilmiy tadqiqotlar sharhi[1]. Quyosh elementlari va ularni tayyorlashda kerakli yarimo‘tkazgich materiallarining fizik va texnologik xossalarini o‘rganish bo‘yicha ilmiy izlanishlar jahonning yetakchi oliy ta’lim muassasalari va ilmiy markazlari, jumladan, Halle, Leipzig, Magdeburg universitetlari (Germaniya), Muqobil energiya milliy laboratoriyasi (NREL, AQSH), Kolorado universiteti (AQSh), Shveytsariya Federal Materialshunoslik va Texnologiyalar laboratoriyalari (EMPA), Parma, Verona universitetlari (Italiya), Yangi Janubiy Uels universiteti (Avstraliya), Xitoy elektron fan va texnologiya universiteti (Xitoy), Kyoto va Ritsumeikan universitetlarida (Yaponiya) olib borilmoqda. Bu sohadagi ilmiy izlanishlar nafaqat universitetlarda, quyosh elementlarini ishlab chiqaruvchi zavodlar tomonidan ham doimiy rivojlantirib borilmoqda. Masalan, “First Solar” (AQSh), “Oxford PV” (Buyuk Britaniya), “CTF Solar”, “AVANCIS”, QCELLs (Germaniya), “Solar Frontier”, Panasonic, Sekisui (Japoniya) zavodlarini keltirish mumkin.

Muammoning o‘rganilganlik darajasi. Hozirgi kunda olimlar tomonidan dunyoning yetakchi ilmiy markazlari va universitetlarida samarali quyosh elementlarini olish borasidagi ilmiy tadqiqotlar o‘rganilmoqda. Jumladan, avstraliyalik olim M. Green tomonidan Si asosida, shvesariyalik olim A. Tiwari $Cu(In,Ga)Se_2$ asosida, germaniyalik olim R. Scheer, yaponiyalik olim T. Minemoto va xitoylik

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[1] Taqdimnoma mavzusi bo‘yicha xorijiy ilmiy tadqiqotlar sharhi https://scholar.google.com/, https:// www.linkedin.com/, https://www.dgfi.unsw.edu.au/, https://www.empa.ch/web/s207, https://www. physik.uni-halle.de/fachgruppen/photovoltaik/, https://www.ritsumei.ac.jp va boshqa manbalar asosida ishlab chiqilgan.

olimlar J. Tang Sb_2Se_3 asosida quyosh elementlarini olish bo‘yicha ilmiy ishlar olib borilmoqda.

Oltmish yildan ortiq vaqt davomida ushbu yuqorida sanab o‘tilgan va boshqa materiallar asosidagi quyosh elementlari ustida ilmiy tadqiqotlar olib borilmoqda. Yuqori samaradorlikka ega quyosh elementlarini amalda tayyorlash imkoni borligi isbotlangan. Hozirgi kundagi bu sohadagi ilmiy muammolar quyosh elementlarini tannarxini yanada pasaytirish, samaradorligini oshirish, turli yengil va egiluvchan tagliklarda tayyorlash kabilarni qamrab olgan.

Belorussiya milliy universitetining Fizika fakulteti dekani M.S. Tivanov boshchiligida yupqa qatlamli quyosh elementlarini olish bo‘yicha ilmiy tadqiqotlar olib borilmoqda. Shuningdek, O‘zbekistonlik olimlardan T.M. Raziqov rahbarligida Fizika-texnika institutida kimyoviy molekulalar dastalaridan olish usuli (KMDO) bilan ikki va ko‘pkomponentli xalkogenidli yarimo‘tkazgichlardan quyosh elementlarini olishning yangi texnologiyasi ishlab chiqilgan.

Biroq, shu kunga qadar binar birikma Sb_2Se_3 va $Cu(In,Ga)Se_2$ asosidagi quyosh elementlarini kimyoviy molekulalar dastalaridan olish usuli yordamida tayyorlash o‘rganilmagan. Shu sababli, Sb_2Se_3 va $Cu(In,Ga)Se_2$ asosidagi quyosh elementlarini olish shartlarini o‘rganish, taqdimnomada tavsiya etilgan usulda olingan quyosh elementlarining elektr va optik xususiyatlariga bog‘liqlik qonuniyatlarini o‘rnatish bo‘yicha olib borilayotgan izlanishlar yarimo‘tkazgichlar materialshunosligi va yarimo‘tkazgichlar fizikasining **dolzarb** vazifasi bo‘lib, fan uchun ham, amaliyot uchun ham katta qiziqish uyg‘otadi.

Dissertatsiya mavzusini ushbu mavzuda dissertatsiya olib borilayotgan oliy o‘quv yurtlari va ilmiy-tadqiqot muassasalarining ilmiy ishlari bilan bog‘lash. Sb_2Se_3 asosidagi ilmiy ishlar O‘zR Fanlar Akademiyasi tomonidan moliyalashtirilgan “Yangi turdagi xalkogenli materiallar asosida yupqa qatlamli quyosh elementlarini kompleks tadqiq qilish va ishlab chiqish” (2021-2024 yy.) mavzusidagi ilmiy loyiha doirasida bajarilgan. $Cu(In,Ga)Se_2$ asosidagi ilmiy ishlar Yaponiyaning Solar Frontier va Toshiba kabi kompaniyalari tominidan qiziqish bildirilgan va moliyalashtirilgan.

Tadqiqot maqsadi. $Cu(In,Ga)Se_2$ va Sb_2Se_3 asosidagi yupqa qatlamli quyosh elementlarini olish va fizik hossalarini tadqiq qilish.

Tadqiqot vazifalari:

vakuum va vakuumsiz muhitlarda Sb_2Se_3 yupqa qatlamlarini olish;

vakuum muhitlarda olingan Sb_2Se_3 yupqa qatlamlarini morfologik va strukturaviy xossalarini tadqiq qilish;

vakuumsiz muhitlarda olingan Sb_2Se_3 yupqa qatlamlarini quyosh elementida foydalanish uchun mos keladigan strukturaviy xossalarini rivojlantirish;

$Cu(In,Ga)Se_2$ asosidagi yupqa qatlamli quyosh elementlarini standart (Mo kontakti ustida tayyorlangan quyosh elementi) struktura asosida olish;

standart strukturada olingan $Cu(In,Ga)Se_2$ yupqa qatlamli quyosh elementlari asosida ikki yuza (bifacial) orqali yorug‘lik qabul qilish imkoniga ega quyosh elementlarini tayyorlash va ularning fotovoltaik xossalarni tadqiq qilish;

ikki yuzali strukturada olingan $Cu(In,Ga)Se_2$ yupqa qatlamli quyosh elementlarini tandem quyosh elementlariga tadbiq qilish samaradorligini nazariy tahlil qilish.

Tadqiqot obyekti kimyoviy molekulalar dastalaridan olish usuli va impulsli, lazerli o‘tkazish (pulsed-laser deposition (PLD)) usullari yordamida olingan Cu(In,Ga)Se_2 va Sb_2Se_3 asosidagi yupqa qatlamli quyosh elementlari.

Tadqiqot predmeti vakuum va vakuumsiz muhitda olingan Sb_2Se_3 yupqa qatlamlari, Cu(In,Ga)Se_2 asosidagi yupqa qatlamli quyosh elementlarini standart va ikki yuzali strukturalari, raqamli modellardan foydalangan holda ikki yuzali- “bifacial tandem” strukturali quyosh elementlarning ishlash samaradorligi tahlillari hisoblanadi.

Tadqiqot usullari. Qo‘yilgan vazifalarni yechish uchun vakuum va vakuumsiz muhitda ishlovchi qurilmalarda yarimo‘tkazgichli yupqa qatlamlar va quyosh elementlari olish, olingan yupqa qatlamlarning strukturaviy xossalarni tadqiq etishda rentgen nurlari difraksiyasi usuli, qatlamlarning sirt relyefini aniqlashda atom kuch mikroskopiyasi va skanerlovchi elektron mikroskopiyasi, zaryad tashuvchilarning xarakatchanligini aniqlashda Xoll metodi, optik xossalarini o‘lchashda zamonaviy fotoakustika va fotokuchlanish usullari, tok o‘tish mexanizmlarini aniqlashda volt-amper xarakteristikalarni tahlil qilish, optik yorug‘lik yutish chegarasini aniqlashda zamonaviy ellipsometriya uslublaridan va boshqa bir qancha zamonaviy metodlardan foydalanilgan.

Tadqiqotning ilmiy yangiligi quyidagilardan iborat:

ilk marta vakuum va vakuumsiz muhitda olingan Sb_2Se_3 yupqa qatlamlarining fizik xossalari orasidagi bog‘liqlik, yani taglikning past T≥300°C haroratlarida olingan Sb_2Se_3 qatlamlari polikristal strukturali (*hkl*, $l \neq 0$) kristal yo‘nalishda taglik yuzasiga perpendikulyar o‘sishi, stexiometrik tarkibda yoki Se ga boy bo‘lishi, elementlarning yuza bo‘yicha tehg taqsimlanishi, taqiqlangan zona kengligi (E_g = 1.12 eV) va solishtirma qarshiligi $10^4 \div 10^6$ Om · șm teng bo‘lishi aniqlangan;

vakuum muhitda taglikning T=250°C haroratida, Argon gazini 2-3 Pa bosimida va 2:3 at.%, 1:4 at.% Sb:Se nisbatli manbalardan olingan Sb_2Se_3 qatlamlari nafaqat (*hkl*, $l \neq 0$), balkim (*hkl*, $l = 0$) cho‘qqilarning intensivligi nisbatan yuqori bo‘lishi, shuningdek, 1:3 at.% Sb:Se nisbatli manbadan olingan Sb_2Se_3 qatlamlari (*hkl*, $l \neq 0$) kristal yo‘nalishda taglik yuzasiga perpendikulyar o‘sishi rentgen strukturaviy tahlil usulida aniqlangan;

vakuum muhitda Sb_2Se_3 yupqa qatlamlarini 300°C dan yuqori bo‘lgan haroratda olish namunadagi “Se” elementini kamayishiga sabab bo‘lishi energiya dispersli rentgen spektroskopiyasi usulida aniqlangan;

vakuumsiz muhitda Sb_2Se_3 olingan yupqa qatlamlarini rentgen nurlari difraksiyasi, skanerlovchi elektron mikroskopiyasi, Xoll metodi va ellipsometriya usullari yordamida tadqiq qilish natijalari asosida samarali quyosh elementlari talablariga mos holda tayyorlashning optimal texnologik rejimlari aniqlangan;

ilk marta Cu(In,Ga)Se_2 asosidagi yupqa qatlamli quyosh elementlarini ikki yuzali holatda o‘tkazish metodini qo‘llash orqali ularning samaradorligini ortishi ko‘rsatib berilgan;

ilk marta ikki yuzali quyosh elementini ko‘p qatlamli strukturada qo‘llash energiya yo‘qolishini sezilarli darajada pasayishi va tandem quyosh elementining samaradorlik quvvatini 62% gacha ortishi ko‘rsatib berilgan.

Tadqiqotning amaliy natijalari quyidagilardan iborat:

samarali quyosh elementi uchun yuqori sifatli Sb_2Se_3 yupqa qatlamlarini vakuumli muhitda, 300℃ dan past haroratda olishning fizik-texnologik asoslari ishlab chiqilgan;

vakuumli muhitda tayyorlangan Sb_2Se_3 yupqa qatlamlarni sirtiy oksidlanish darajasi o‘rganilgan, shuningdek, Sb_2Se_3 yupqa qatlamlarini yuzasida oksid qatlami hosil bo‘lmasligi aniq tajribalar asosida ko‘rsatib berilgan;

tajriba ma’lumotlarini tahlil qilish asosida ikki yuzali Cu(In,Ga)Se_2 asosidagi yupqa qatlamli quyosh elementlarini rivojlantirish – quyosh nurini ikki (yuqori va quyi) sirtlardan qabul qilish imkonini bergan. Bu o‘z navbatida ko‘proq quyosh nurini yutilishiga va quyosh elementini ishlash samaradorligini ortishiga olib kelgan;

ikki yuzali Cu(In,Ga)Se_2 asosidagi yupqa qatlamli quyosh elementlarini olishning fizik-texnologik asoslari ishlab chiqilgan;

ikki yuzali Cu(In,Ga)Se_2 asosidagi yupqa qatlamli quyosh elementlarini yengil vaznli va egiluvchan polimer taglikda olish imkoniyati ko‘rsatilgan;

Mo metal tagligi va Cu(In,Ga)Se_2 yupqa qatlami orasida hosil bo‘luvchi $MoSe_2$ qatlamining fizik xossalarini boshqarishning fizik-texnologik asoslari ishlab chiqilgan. Natijada Mo va Cu(In,Ga)Se_2 sirt chegarasida energiya yo‘qotishlari bartaraf etilib, Cu(In,Ga)Se_2 asosidagi yupqa qatlamli quyosh elementlarining samaradorligi ortishiga erishilgan.

Tadqiqot natijalarining ishonchliligi matematik fizika, hisoblash matematikasi va yarimo‘tkazgichlar fizikasining zamonaviy tasdiqlangan usullarini qo‘llash orqali ta’minlangan. Namunalar yarimo‘tkazgichli moddalarni tayyorlashda keng qo‘llaniladigan texnologiyalar asosida olingan. Natijalar qat’iy ravishda umumiy klassik va kvant fizikaning matematik apparati doirasida tahlil etilgan. Hisoblashning zamonaviy raqamli va analitik usullari ham qo‘llanilgan va natijalar mavjud ma’lumotlar va boshqa mualliflarning natijalari bilan taqqoslangan. Ishning xulosalari quyosh elementlari va yarimo‘tkazgichlar fizikasining asosiy qoidalariga mos keladi.

Tadqiqot natijalarining ilmiy va amaliy ahamiyati. Tadqiqot natijalarining ilmiy ahamiyati yangi yarimo‘tkazgichli element yoki birikmalar asosida samarali quyosh elementlarini shakllantirishdan iborat. Bundan tashqari, hozirda mavjud quyosh elementlarini yanada takomillashtirish – ikki tomonlama quyosh nurini qabul qila oladigan qilib tayyorlash ularni ishlash samaradorligini yanada ortishiga hizmat qiladi.

Tadqiqot natijalarining amaliy ahamiyati shundaki, tadqiqot ilmiy ishlaridan olingan asosiy natijalar kelgusida ekologik toza, arzon va yuqori samarali yupqa qatlamli quyosh modullarini sanoat miqyosida keng ko‘lamda ishlab chiqishni yanada rivojlanishiga turtki beradi.

Tadqiqot natijalarini joriy qilinishi.

Cu(In,Ga)Se_2 va Sb_2Se_3 yupqa qatlamlari va ular asosidagi quyosh elementlarini rivojlantirish bo‘yicha bajarilgan ilmiy natijalar xorijiy tadqiqotchilarning ishlarida, yani yupqa qatlamli quyosh elementlarini fizik xossalarini tushuntirish va samaradorligini oshirishda ishlatilgan. Tadqiqotning Ilmiy ishlariga “Web of Science” va “Scopus” bazalarida berilgan iqtibosliklar ro‘yxati 1000 dan ortiq bo‘lib (2023 yil Oktyabr holati), shulardan bir qismi quyida keltirilgan:

Turli tarkibli Sb_2Se_3 yupqa qatlamlarning morfologik, strukturaviy, optik va elektr xususiyatlarini oʻrganish asosida olingan natijalar Sb_2Se_3 qatlamlarining parametrlarini optimallashtirishga xizmat qilgan. Bu natijalar xorijiy jurnallarda surma selenid qatlamlari va ular asosidagi quyosh elementlarining elektr va optik xususiyatlarini oʻrganishga bagʻishlangan quyidagi tadqiqotlarda qoʻllanilgan: (Solar Energy Materials and Solar Cells. Impact Factor: 7,267. Vol. 200, 15 September 2019, 109945; Solar Energy, Impact Factor: 5,95. Vol. 187, 15 July 2019, Pages 404-410; Solar Energy, Impact Factor: 5,95. Vol. 188, August 2019, Pages 586-592). Olingan ilmiy natijalar qatlam tayyorlashdagi ilmiy-texnik va texnologik jarayonlarda qoʻllanilishi natijasida Sb_2Se_3 qatlamining morfologiyasi va tuzilmasini yaxshilash imkonini bergan. Buning natijasida Sb_2Se_3 asosida 5,6 % samaradorlikli yupqa qatlamli quyosh elementi yaratilgan.

Cu(In,Ga)Se_2/ITO yuzasida vujudga kelishi kuzatilgan kontakt qarshiligi va elektr potensialini mavjudligi boshqa turdagi yarimoʻtkazgich materiallari asosidagi quyosh elementlarida ham tushuntirib berish imkonini bergan. Xususan, Sb_2Se_3/Fe_2O_4(FeS) yuzasini rivojlantirishda qoʻllanilgan (Solar Energy, Impact Factor: 6,7. Vol. 249, 1 January 2023, Pages 414-423). Bundan tashqari, yarim-shaffof optik hususiyatga ega Cu(In,Ga)Se_2/ITO asosidagi quyosh elementlarini rivojlantirish va ularni chidamliligini oshirishda foydalanilgan (Solar RRL, Impact Factor: 8,31. Vol. 6, 17 February 2022, 2101071). Shuningdek, p-tipdagi CZTSSe asosidagi quyosh elementlarini samaradorligini oshirishda foydalanilgan (Journal of Materials Science: Materials in Electronics, Impact Factor: 2,48. Vol. 32, 7 August 2021, Pages 22535-22547). Keng taqiqlangan energiyaga ega quyosh elementlarida ITO dan foydalanish mumkinligini aniqlashda foydalanilgan (Solar RRL, Impact Factor: 8,31. Vol. 6, 18 May 2022, 2200401). Eng muhimi, kimyoviy usulda tayyorlangan Cu(In,Ga)Se_2/ITO yuzasidan foydalangan holda ham samarali quyosh elementi olish mumkinligini aniqlanishiga asos boʻlgan (Advanced Materials Interfaces, Impact Factor: 6,39. Vol. 10, 1 September 2023, 2300566).

Cu(In,Ga)Se_2/Mo yuzasida vujudga keluvchi $MoSe_2$ qatlamiga bagʻishlangan ilmiy tadqiqot natijalari quyosh elementidagi V_{oc} ni 100 mV ga oshirishga, orqa yuzada vujudga kelgan sigʻim qarshiligini pasaytirishda, va past haroratlarda samarali quyosh elementlarini tayyorlashda foydalanilgan (Nature Energy, Impact Factor: 27,05. Vol. 8, 21 November 2022, Pages 40-51; Advanced Functional Materials, Impact Factor: 19,41. Vol. 33, 20 July 2023, 2303188; Progress in Photovoltaics: Research and Applications, Impact Factor: 8,05. Vol. 30, 21 October 2021, Pages 191-202). Bundan tashqari Sb_2S_3 quyosh elementlarida ham Mo tagligidan foydalanish uchun qoʻllanilgan (Advanced Science, Impact Factor: 17,52. Vol. 10, 5 September 2023, 2303414).

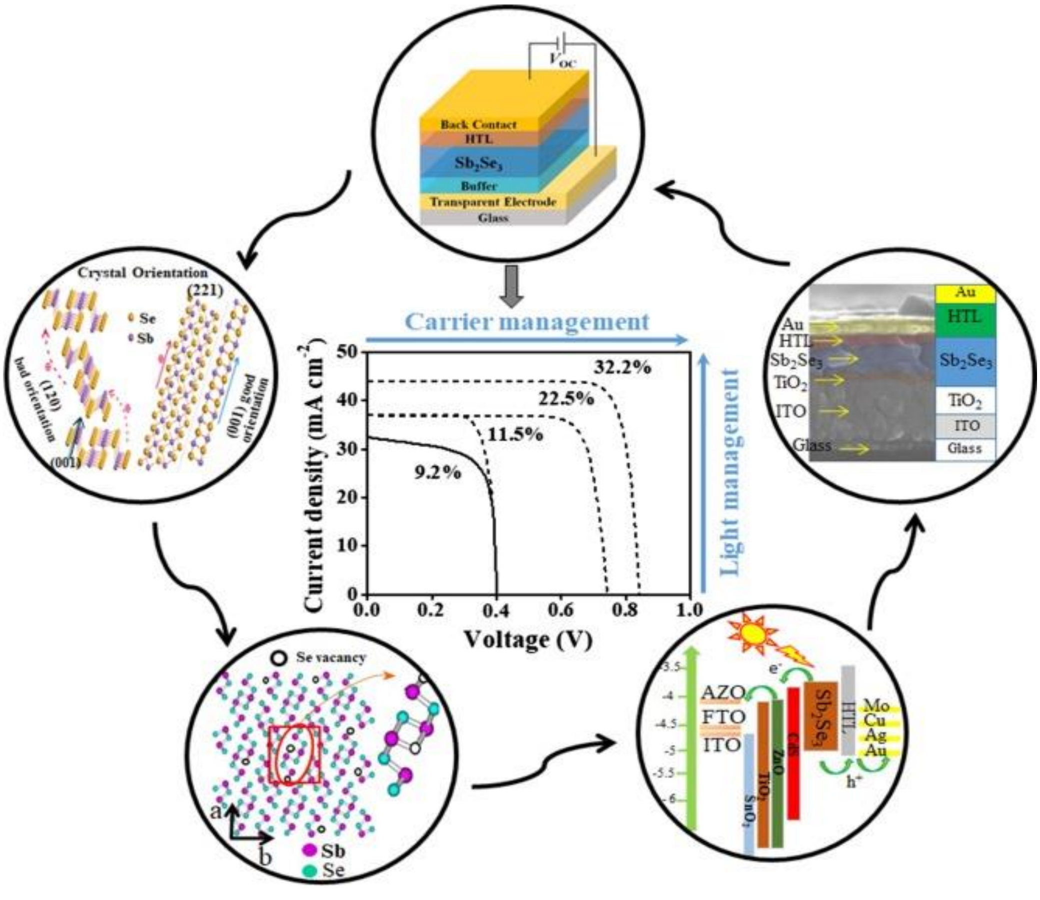
Tadqiqot natijalarini nashr etish. DSc tadqiqoti natijalari Oʻzbekiston Respublikasi Oliy ta’lim, fan va innovatsiyalar vazirligi huzuridagi Oliy attestatsiya komissiyasi tomonidan tavsiya etilgan nufuzli Q1/Q2 tipdagi ilmiy jurnallarida chop etilgan 35 ta ilmiy maqolalarda oʻz aksini topgan.

ISHNING ASOSIY TARKIBI

I qism.

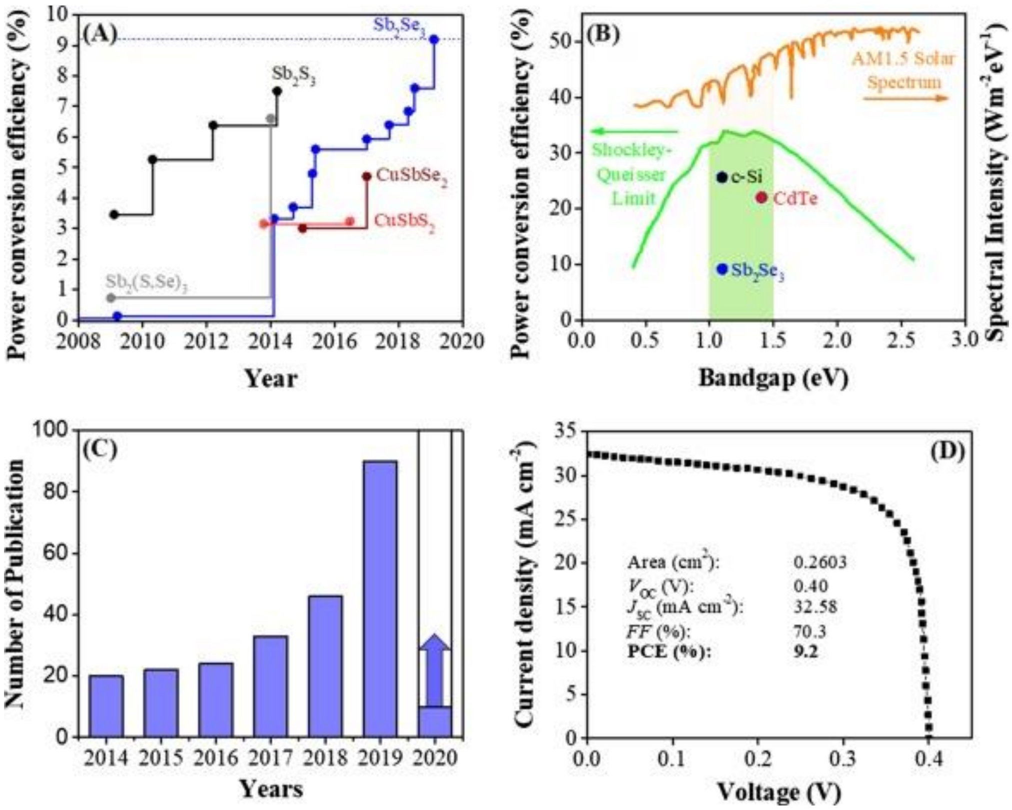
Surma selenid (Sb_2Se_3) noorganik V_2-VI_3 birikmalari oilasiga tegishli yarimo‘tkazgichli birikma hisoblanadi (Bi_2S_3, Bi_2Se_3, Bi_2Te_3, Sb_2S_3, Sb_2Se_3, Sb_2Te_3). Sb_2Se_3 birikmalari tabiiy ravishda stibnit minerali shaklida mavjud bo‘lib, ortorombik tuzilishga ega va [001] yo‘nalishda parallel ravishda biriktirilgan $(Sb_4Se_6)_n$ tasmalar tomonidan hosil bo‘ladi. Ushbu materiallarning o‘xshash tuzilishga egaligiga qaramasdan, ulardan faqat bir nechtasi, masalan, Sb_2S_3, Bi_2S_3 va Sb_2Se_3 – quyosh elementlari uchun qo‘llanishi mumkin. Umuman olganda, nazariy hisob-kitoblar Sb_2Se_3 asosidagi quyosh elementlari V_2-VI_3 birikmalari orasida yuqori potentsialga ega ekanligini ko‘rsatgan.

Sb_2Se_3 quyosh elementi va fotokataliz sifatida foydalanish uchun foydali birikma ekanligi soha olimlarida katta qiziqish uyg‘otdi. Yer qobig‘ida Sb va Se elementlarining ko‘pligi mos ravishda 0,2 va 0,05 ppm va Sb_2Se_3 yaxshi fizik-kimyoviy barqarorlikka ega. 1-rasmda so‘nggi tadqiqot yutuqlari, shuningdek, Sb_2Se_3 asosidagi yupqa qatlamli quyosh elementlarining kelajakdagi tadqiqot yo‘nalishlari ko‘rsatilgan.



1-rasm. Sb_2Se_3-asosidagi quyosh elementlarini muhim tadqiqot yo‘nalishlari. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: back contact – orqa qismdagi metal kontakt; transparent electrode – shaffof elektr tashuvchi qatlam; glass – oyna taglik; crystal orientation – kristal struktura yo‘nalishi; bad orientation – yomon kristal yo‘nalishi; good orientation – yaxshi kristal yo‘nalishi; Se vacancy – “Se” elementini vakant (bo‘sh) o‘rni; carrier management – zaryad tashuvchi (electron)larni boshqarish/rivojlantirish; light management – yorug‘lik (yutilishi)ni boshqarish/rivojlantirish; current density – elektr toki zichligi; voltage – elektr kuchlanishi.

1-rasmda ko‘rsatilganidek, quyosh elementini samaradorligini oshirish uchun (221) kristall yo‘nalishi va xususiy nuqtaviy nuqsonlar zichligini kamaytirish talab qilinadi. Nuqsonlar orasida Se vakansiyalarini (V_{Se}) kamaytirish muhim hisoblanadi. Umuman olganda, Sb_2Se_3 o‘zining qulay fizikaviy xususiyatlari va ular asosidagi quyosh elementlarining samaradorligini tez sur’atlarda ortib borishi tufayli olimlar hamjamiyatida bu birikma tadqiqotiga qiziqish ortib bormoqda. So‘nggi o‘n yil ichida Sb_2Se_3 va unga turdosh materiallar asosidagi quyosh elementlari bo‘yicha 200 dan ortiq maqolalar nashr etilgan (2-rasm).



2-rasm. Sb_2Se_3 va Sb_2S_3 asosidagi quyosh elementlari ko‘rsatgan natijalar va chop etilgan maqolalar soni keltirilgan. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: power conversion efficiency – (qushosh elementini) foydali ish koeffisienti; year(s) – yil(lar); bandgap – (yarimo‘tkazgich qatlamni) ta’qiqlangan zona kengligi; spectral intensity – spektr intensivligi (quyosh nurini foton energiyasiga mos holda taqsimlanishi); Shockley-Queisser Limit – Shokley-Qviser limiti; AM1.5 Solar Spectrum – Quyosh nuri AM1.5 holatdagi spektri; number of publication – maqolalar soni; current density – elektr tok zichligi; voltage – elektr kuchlanishi; area – (quyosh elementi) yuzasi.

1.1. Sb_2Se_3 kristal tuzilishi va fizik xossalari

Sb_2Se_3 Pnma (62) kristal guruhiga tegishli bo‘lgan ortorombik tuzilishda (1-rasm) kristallanadi. Sb_2Se_3 ning kristall strukturasi parametrlari bir nechta tadqiqot guruhlari tomonidan hisoblab chiqilgan va o‘lchangan. Sb_2Se_3 kristal panjara o‘lchamlari a = 11,62 ± 0,01 Å, b = 3,962 ± 0,007 Å va c = 11,77 ± 0,01 Å bo‘lib, eng kichik hujayra hajmi 0.524 nm^{-3} ga teng. Bog‘langan Sb-Se ning masofalari 2,576 Å dan 2,777 Å gacha, bog‘lanmagan Sb-Se ning masofalari esa 2,98 Å dan boshlanadi. Se-Sb-Se va Sb-Se-Sb burchaklari mos ravishda 86,6° va 96,0° va 91,0° va 98,9° ga teng. Sb_2Se_3 tuzilishi *c* o‘qi bo‘ylab Se-Sb-Se zanjirlaridan iborat. Ya’ni, Sb_2Se_3 kristali Sb_4Se_6 birliklaridan hosil bo‘lgan bir o‘lchovli (1D) lentalardan tashkil topgan kristall tuzilishga ega, ushbu lentalar o‘zaro zaif Se-Se ta’sirlari bilan bog‘langan. Stereokimyoviy faol Sb s^2 bog‘lari Sb atrofida kvadrat piramidal koordinatsiyaga olib keladi; Shunday qilib, bu lentalar orasidagi bo‘sh joyni egallaydi. Umuman olganda, 1D kristal topologiyasi Sb_2Se_3 ning yuqori samarali quyosh elementi uchun asosiy afzalliklaridan biridir. Boshqacha qilib aytganda, Sb_4Se_6 birliklaridan hosil bo‘lgan 1D lentalar orasidagi bog‘lanishlar lentalar ichidagi bog‘lanishlarga nisbatan kuchsizroq bo‘lib, elektronlarning harakatidagi anizotropik xususiyatni asosiy sababidir. 1D tuzilishi tufayli, lentalarga parallel ravishda hosil bo‘lgan chegaralari (“grain boundary”) zaryad tashuvchilarning (free electrons) rekombinatsiyasini kamaytirish uchun tabiiy ravishda yaxshi bo‘ladi. Bu, ayniqsa, uch o‘lchamli (3D) bog‘lanishga ega polikristal strukturali quyosh elementlarida mavjud. Nazariy hisoblashlar (Density Functional Theory) bo‘yicha o‘tkazilgan tadqiqotlar shuni ko‘rsatdiki, Sb_2Se_3 donalari chegaralari elektr jihatdan yaxshi o‘tkazuvchidir.

Kristalning (001) ortogonal yuzalari, masalan, (010), (110) va (120) sirtlar eng past sirt energiyalariga egaligi hisoblab chiqilgan. Bundan tashqari, Sb_2Se_3 qatlamlarining o‘rtacha sirt potentsiali 9,1 mV ekanligi aniqlangan bo‘lib, bu CIGS yoki CZTS (> 100 mV) dan keskin past. Shunday qilib, Sb_2Se_3 da, agar sirtlar mos ravishda yo‘naltirilgan $[Sb_4Se_6]_n$ lentalari bilan tugatilgan bo‘lsa, Sb_2Se_3 da nuqsonlarda rekombinatsiya yo‘qotilishini minimum darajada kamaytirish mumkin. 3D polikristalli yupqa qatlamli quyosh elementlarida zaryad tashuvchilarning rekombinatsiyasi passivatsiya yo‘li bilan kamaytirilishi mumkin.

Taqqoslash uchun, Sb_2Se_3 da bunday passivatsiya talab etilmaydi, ammo yupqa qatlamning yo‘nalishini nazorat qilish orqali, anizotropik xususiyatlar tufayli, yuqori samaradorlikka ega quyosh elementlariga erishishning asosiy omillaridan biridir. Yuqorida aytib o‘tilganidek, Sb_2Se_3 ning 1D anizotropik strukturasi elektr zaryadni samarali tashish xususiyatlarini keltirib chiqaradi. Umuman olganda, Sb_2Se_3 p-tip elektr o‘tkazuvchanlikka ega va bu quyosh elementi uchun muvofiq hisoblanadi. Biroq, ba’zi Sb_2Se_3 namunalari Te, Bi kabi kirishmalar bo‘lsa, n-tipidagi o‘tkazuvchanlikni ko‘rsatadi. Bundan tashqari, selen bo‘shlig‘i (V_{Se}) kabi Sb_2Se_3 ning xususiy nuqsonlari ham n-tipidagi nuqson hosil qiladi, ya’ni ekertron donorlik xususiyatiga ega. P-tipidagi Sb_2Se_3 quyosh elementlari uchun ishlatilganligi sababli, namunalarni p-tipda tayyorlash maqsadga mufoviq.

Sb_2Se_3 namunalarining qorong‘u va yoritilgan o‘tkazuvchanlik qiymatlari mos ravishda 2×10^{-8} va 1×10^{-6} $(\Omega\ cm)^{-1}$ ni tashkil etdi. Zaryad tashuvchilar (musbat zaryadli kovaklar) 22 $cm^2V^{-1}s^{-1}$ harakatchanligi aniqlangan bo‘lib, bu CZTS (10 $cm^2V^{-1}s^{-1}$) yoki PbSe (<1 $cm^2V^{-1}s^{-1}$) dan ham yuqori. Shunga qaramay, maksimal harakatchanlik va minimal rekombinatsiyani saqlab qolish orqali quyosh elementlari samaradorligini oshirish uchun 1D kristall donalarini yo‘naltirish muhim ahamiyatga ega. Shu bilan birga, samarali quyosh elementlari uchun erkin zaryad tashuvchilar zichligi ~ 10^{13} cm^{-3} dan 10^{16} cm^{-3} gacha bo‘lgan optimal qiymatdan pastroq bo‘lib, Sb_2Se_3 da erkin zaryad tashuvchilar zichligini oshirish maqsadga muvofiq.

Sb_2Se_3 ustidagi dastlabki ishlarda Sb_2Se_3 kristallarning faollashuv energiyasi (activation energy, E_a) keng energetic sohada (0.2÷1.0 eV) o‘zgarishi aniqlangan. Bu o‘zgarish 0.54÷0.66 eV oralig‘ida energiya bo‘shlig‘ida boshqa holatda biriktirilgan Fermi sathidagi farq yoki Sb_2Se_3 namunalarida qalinligiga bog‘liqligi aniqlangan.

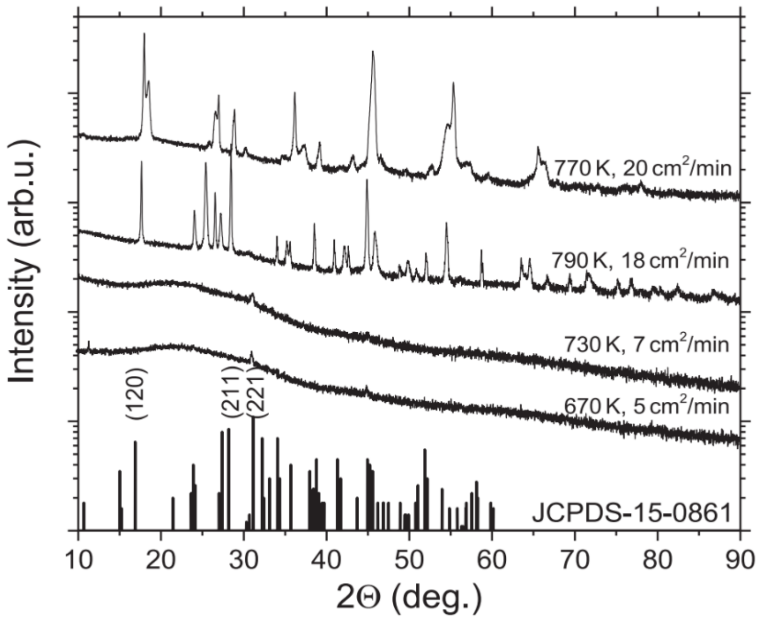
Faollashtirish energiyasi kimyoviy tarkib bilan ham bog‘liqligi aniqlangan bo‘lib, Sb_xSe_{1-x} namunalarida x ni qiymati 0.0 dan 0.9 gacha bo‘lganda, E_a 1.0 eV dan 0.2 eV gacha pasayishi aniqlangan. Xabar qilingan yuqori faollik energiyasi chuqur sathli nuqsonlarning energetik sathlari mavjudligini ko‘rsatadi. Shularni hisobga olgan holda o‘stirilgan Sb_2Se_3 qatlamlaridagi asosiy nuqson zichligi taxminan 10^{14} cm^{-3} ekanligi aniqlandi, bu CdTe asosidagi quyosh elementlaridagidan yuqori (10^{11} dan 10^{13} cm^{-3} gacha). Xulosa qilib aytganda, V_{OC} ni oshirish va quyosh elementi samaradorlini yaxshilash uchun ushbu chuqur sathli nuqsonlar zichligini kamaytirish talab etiladi.

1.2. Vakuumsiz usulda Sb_2Se_3 namunalarini o‘stirish.

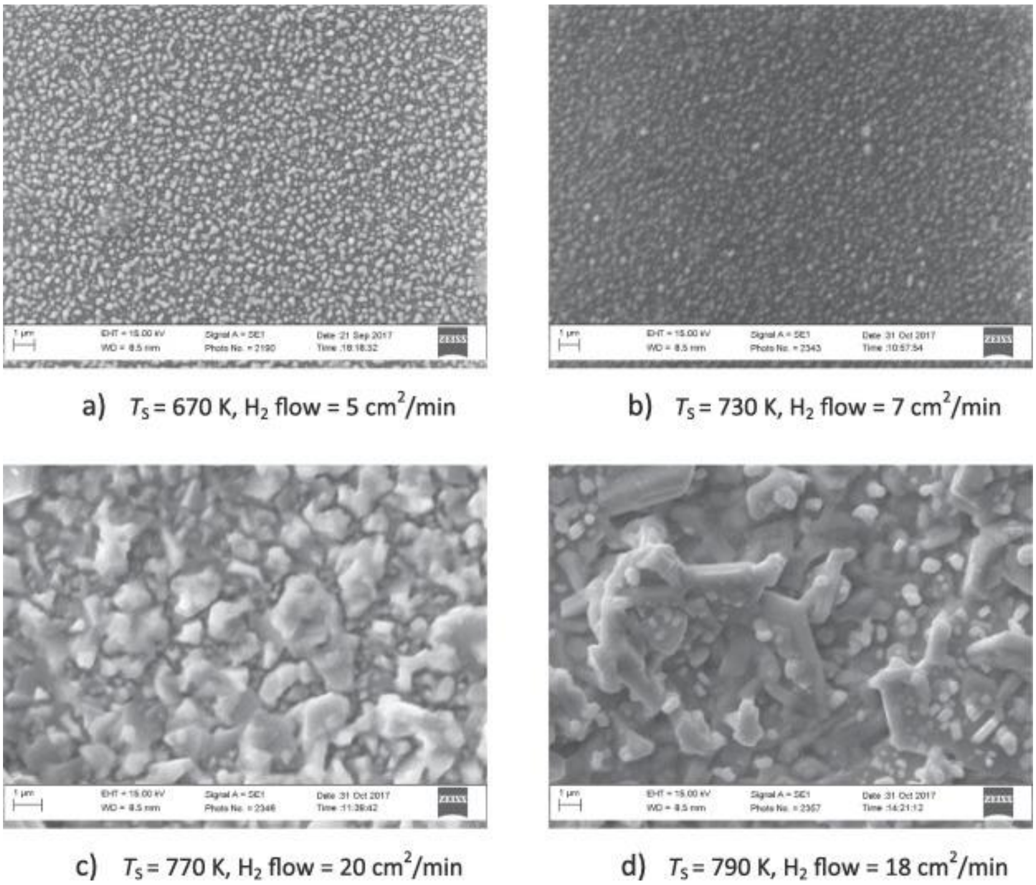
Sb_2Se_3 namunalarini vakuumsiz muhitda o‘stirish quyosh elementini tan narxini pasaytirish uchun samarali yo‘nalishlardan biri hisoblanadi. Shu nuqtai nazardan, Sb_2Se_3 namunalari birinchi marta kimyoviy molekulalar dastalaridan olish usuli bilan olindi. Yuqorida sanab o‘tilgan samarali quyosh elementi olish uchun zarur fizik xossalari o‘rganildi.

Ya’ni, Sb_2Se_3 namunalarining morfologik va strukturaviy xususiyatlari o‘rganildi va ularni samarali boshqarish yo‘llari aniqlandi. Bu maqsadda, Sb_2Se_3 namularini turli bosqichdagi taglik haroratida, tashuvchi vodorod gazini oqimi tezligining funktsiyasi sifatida tartibli o‘rganildi.

Tajriba ma’lumotlar shuni ko‘rsatdiki, vodorod oqimi past bo‘lganda, Sb_2Se_3 namunalari Se-boy holatda o‘sadi va namunalar asosan amorf strukturada bo‘ladi. Biroq, bu holatda, Sb_2Se_3 namunalarini kristal strukturasi kichik (221) cho‘qqilarni ko‘rsatdi. Bundan farqli o‘laroq, vodorod oqimining yuqori tezligida qatlamlar Sb ga boy tarkibga va polikristal strukturaga ega bo‘lib o‘sishi, va (211) yo‘nalishlarni intensivligi ortishi kuzatildi (3-rasm). Sb ga boy holatda namunalarni o‘sishi yuqori taglik harorati bilan bog‘liq bo‘lib, buni namunadan Se ning qayta bug‘lanishi bilan tushuntirish mumkin (4-rasm).



3-rasm. Vakumsiz usulda belgilangan taglik haroratida turli xil vodorod oqim tezligida o‘stirilgan Sb_2Se_3 qatlamlarining Rentgen nurlari diffraktsiyasi ma’lumotlari. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: intensity – intensivligi; deg. (=degree) – (burchak) gradusi.

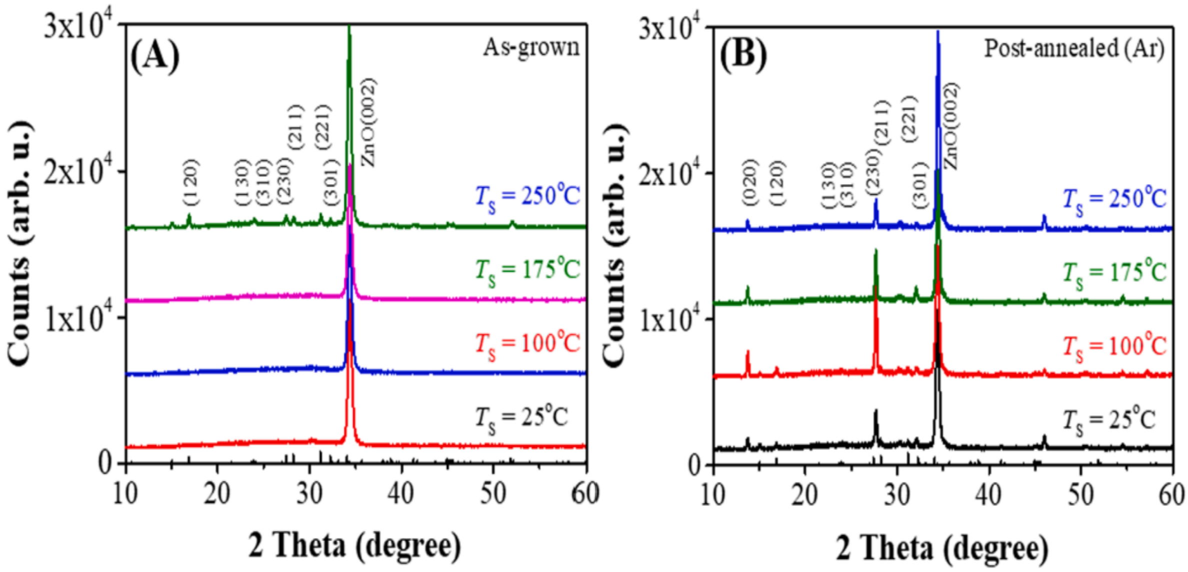


4- rasm. (a, b) Kichik vodorod oqimi tezligi (5-7) cm^2 / min va (c, d) yuqori vodorod oqim tezligida (18-20) cm^2 / min o‘stirilgan Sb_2Se_3 namunalarining SEM tasvirlari. Rasmlar 8.5 mm ish masofasi bilan 15 kV tezlashuv kuchlanishida qayd etilgan.

Polikristal Sb_2Se_3 namularini elektr va optik xususiyatlari *p*-tipidagi o‘tkazuvchanlikni va yuqori yutish koeffitsienti (10^5 cm^{-1}) hamda 1.1 eV qiymatli optik taqiqlangan soha kengligiga egaligi aniqlandi. Ushbu tajriba natijalar vakuumli usulda o‘stirilgan Sb_2Se_3 namularini fizik xususiyatlari bilan mos keladi, va yupqa qatlamli quyosh elementlari uchun muvofiq hisoblanadi.

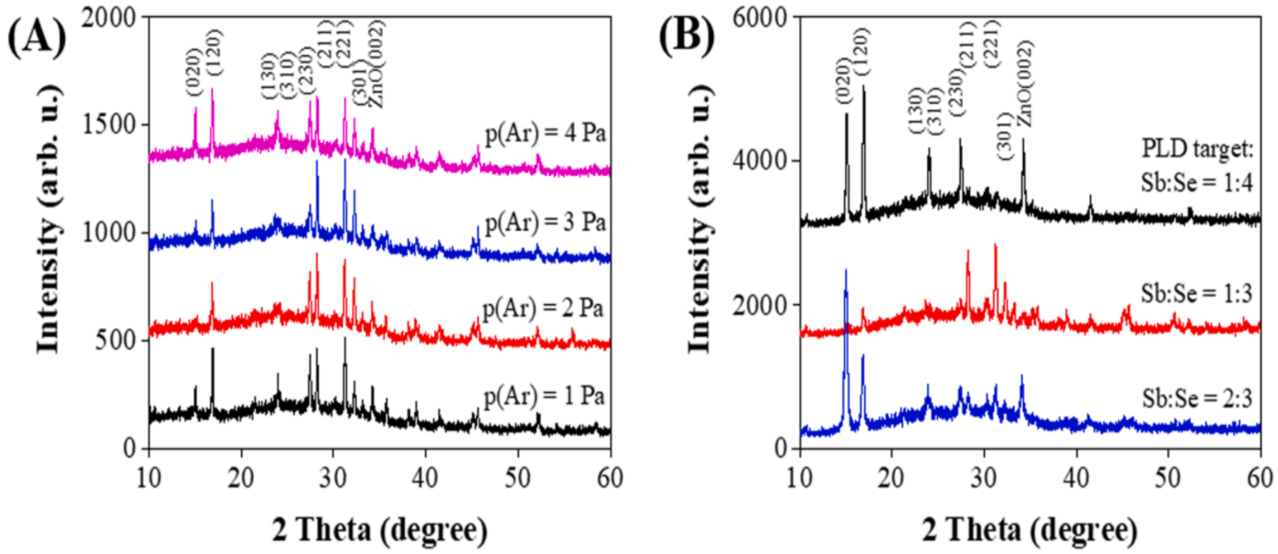
1.3. Vakuum muhitda Sb_2Se_3 namunalarini o‘stirish.

5A rasmda turli taglik temperaturalarida vakuum sharoitida impulsli lazerli o‘tkazish (PLD) usulida o‘stirilgan Sb_2Se_3 yupqa qatlamlarining Rentgen nuri spektrlari tasvirlangan. Ko‘rsatilgandek, past haroratda o‘stirilgan (175℃ gacha) namunalar amorf strukturada bo‘ladi. Yuqoriroq taglik haroratida (250℃), namunalar polikristal strukturada o‘sadi, ya’ni barcha Rentgen nuri diffraktsiya cho‘qqilari Sb_2Se_3 ning ortorombik fazasiga mos indekslanadi (JCPDF # 15-0681). Biroq, bu namunada nafaqat quyosh elementi uchun foydali cho‘qqilar, ya’ni (*hkl*, $l \neq 0$), balki foydasiz (*hkl*, $l = 0$) cho‘qqilar ham namoyon bo‘lgan. 300÷400℃ oralig‘idagi taglik haroratlari uchun namunalar maqsadli kimyoviy tarkibdan qat’i nazar, asosan noqulay (*hkl*, $l = 0$) cho‘qqilar bilan o‘sishi aniqlandi. Bundan tashqari, 300℃ dan yuqori taglik haroratida o‘stirilgan Sb_2Se_3 yupqa qatlamlari stexiometrik nisbatga nisbatan past kimyoviy tarkibga ega, bu Se elementining namunadan qayta bug‘lanishi bilan bog‘liq bo‘lishi mumkin. Bu vakuum kamerasining (inside the PLD chamber) ifloslanishiga va kameraning "kirish oynasi" ning Se qatlami bilan qoplanishiga olib keladi.



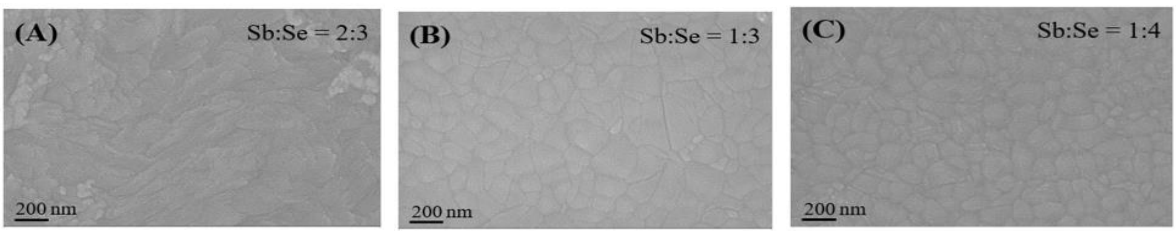
5-rasm. (A) PLD usuli bilan ko‘rsatilgan taglik haroratida o‘stirilgan, va (B) tez termal toblash tizimi yordamida Ar atmosferasida 5 daqiqa davomida 400℃ haroratda qizdirilgan Sb_2Se_3 namunalarining Rentgen difraksiya spektri. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: counts – signal intensivligi soni (raqamlarda); as-grown – yangi tayyorlangan holatdagi namunalar uchun; post-annealed (Ar) – argon gaz muhitida qizdirilgan namunalar uchun; 2 theta (degree) – rentgen nuri difraksiyasi usulida nurning namuna sirtiga nisbatan burchagi (gradusda).

Shunday qilib, 300°C dan past bo‘lgan taglik haroratida Sb_2Se_3 yupqa qatlamlarini vakuum sharoitida o‘stirish lozimligi tasdiqlandi. 5B-rasmda turli Ar gazi bosimida olingan Sb_2Se_3 qatlamlarning Rentgen nuri spektri ko‘rsatilgan. Amorf fazadan polikristal fazaga aniq o‘tish kuzatilganiga qaramay, asosan intensivlik ortishi “keraksiz” (*hkl*, l = 0) kristal yo‘nalishlarda kuzatildi, bu (230) uchun sezilarli. Adabiyotda bu qonuniyat yuqori harorat bilan bog‘liq edi. Yuan va boshqalar toblanish haroratining 320÷440°C oralig‘ida ortishi asosan (110), (020), (120), (230) va (240) intensivligi oshishini aniqladilar. Li va boshqalar ham 330℃ haroratda Sb_2Se_3 qatlamlarni (*hkl*, l = 0) ga ega kristal yo‘nalishlarda o‘sishini tasdiqladilar. Bu (*hkl*, l=0) kristall orientatsiyalar, xususan, (120) quyosh elementlarining elektr qarshiligi ortishiga sabab bo‘lgani tufayli, uni oldini olish kerak. N_2 gazi bosimi ostida ham Ar gasi kabi bir xil natijalar olindi. Yuqoridagi o‘tkazilgan tajribalar kristall yo‘nalishini yaxshilash uchun yetarli bo‘lmaganligi sababli, ayniqsa, pastroq taglik haroratida o‘stirilgan Sb_2Se_3 qatlamlar amorf strukturada o‘sganligi sababli, ushbu namunalar keyinchalik 250℃ haroratda, turli Ar bosimida qisqa muddatga (5min. “rapid thermal annealing” usulida) qizdirildi. 6A-rasmda Sb:Se nisbati 1:4 at.% bo‘lgan manba yordamida turli Ar bosimi ostida o‘stirilgan Sb_2Se_3 yupqa qatlamlar uchun Rentgen nuri spektrlari tasvirlangan. Ko‘rinib turibdiki, qulay cho‘qqilarning intensivligi, ya’ni (*hkl*, $l \neq 0$) kristal yo‘nalish intensivliklari Ar bosimi tasirida o‘zgargan, bu erda 2 va 3 Pa oralig‘idagi Ar bosimi ostida o‘stirilgan qatlamlarda (211) va (221) kristal yo‘nalishlar intensivligi (120) cho‘qqiga nisbatan yuqori holatda bo‘lishiga erishildi.



6-rasm. (A) PLD usuli bilan o‘stirilgan Sb_2Se_3 namunalarining XRD spektri: (A) turli Ar bosimi ostida, va (B) o‘zgarmas Ar qisman bosimi (2.5 Pa) uchun 3 xil elementlar tarkibdagi manbalar asosida olingan namunalar. Barcha Sb_2Se_3 namunalar 300℃ taglik haroratida ZnO/shisha tagliklarida o‘stirilgan. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: Intensity – signal intensivligi (raqamlarda); PLD target – PLD manbasi; 2 theta (degree) – roentgen nuri difraksiyasi usulida nurning namuna sirtiga nisbatan burchagi (gradusda).

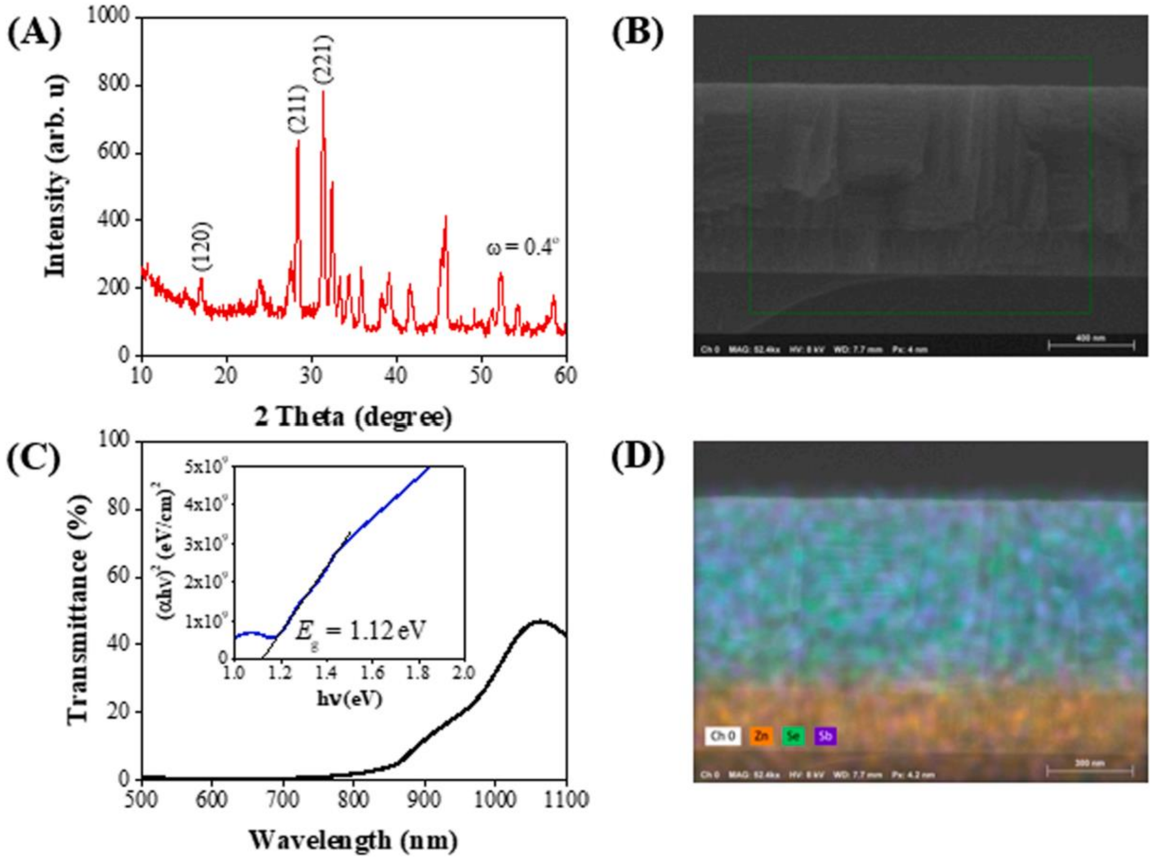
Keyingi holatlarda, Sb_2Se_3 yupqa qatlamlari 2.5 Pa Ar bosimi ostida o‘stirildi. 6B-rasmda uchta turli tarkibga ega manbalardan foydalangan holda 250° haroratda olingan Sb_2Se_3 qatlamlarining Rentgen nuri spektrlari ko‘rsatilgan, ya’ni manbalardagi Sb:Se nisbati 2:3 at.%, 1:3at. % va 1:4 at.% ga teng. Bundan, manbalar tarkibi ham kristallografik fazalarning shakllanishiga sezilarli ta’sir ko‘rsatishi aniqlandi. Stexiometrik nisbatga ega manba uchun (Sb:Se nisbati 2:3 at.%) nafaqat (*hkl*, $l \neq 0$), balkim (*hkl*, $l = 0$) kristal yo‘nalishlar ham kuzatildi, va (*hkl*, $l = 0$) cho‘qqilarning intensivligi nisbatan yuqori bo‘lishi kuzatildi. Xususan, (020) va (120) cho‘qqilar eng yuqori intensivlikni ko‘rsatdi. Boshqa manba (Sb:Se nisbati 1:3 at.%) asosida olingan namunalarda, asosan (*hkl*, $l \neq 0$) kristal yo‘nalishlar bilan o‘sdi. Ular orasida eng yuqori intensivlik (211) va (221) yo‘nalishlarga to‘g‘ri keldi. Eng yuqori Se tarkibiga ega bo‘lgan manba uchun (Sb:Se = 1:4 at.%), faqat (*hkl*, $l = 0$) cho‘qqilari olingan. Ko‘rinishidan, Sb_2Se_3 quyosh elementiga mos kristal strukturada tayyorlash uchun nafaqat taglik harorati, balki Ar gazi bosimi va manbadagi Sb:Se nisbati ham hisobga olinishi kerak. Bularni hisobga olib, eng yaxshi holatda (namunalar 250° taglik harorati, 2.5 Pa Ar bosimi, va 1: 3 at.% Sb:Se nisbatiga ega manba) olingan namunaning fizik hossalari o‘rganildi.



7-rasm. Turli Sb:Se nisbatiga (at.%) ega PLD manbalari asosida tayyorlangan Sb_2Se_3 qatlamlarining SEM tasvirlari: (A) 2:3; (B) 1:3; va (C) 1:4.

7-rasmda 6B-rasmda muhokama qilingan Sb_2Se_3 yupqa qatlamlarining FESEM (field effect scanning electron microscope) tasvirlari keltirilgan. Sb:Se ning manbadagi nisbati 2:3 at.% bo‘lganda, (*hk*0) yo‘nalishlari ustuvor edi (6B-rasm), bu yerda 1D $(Sb_4Se_6)_n$ kristal lentalari taglik yuzasiga parallel ravishda o‘sganini bildiradi. FESEM tasvirida, bu moyillik kristall donalari turli o‘lcham va shaklda o‘sganini ko‘rish mumkin. Sb:Se = 1:3 at.% holat uchun aniq kristall donalari tasvirlangan, bu Rentgen nuri difraksiyasi natijalari bilan mos keladi. Eng yuqori Se konsentrasiyasiga ega bo‘lgan manba uchun, ya’ni Sb:Se = 1:4 at.%, Sb_2Se_3 kristal donalar aralashgan holatini ko‘rish mumkin. Boshqacha qilib aytganda, 7A va 7B-rasmda kuzatilgan donalarning ikkala shakli 7C-rasmdagi namunada mavjud bo‘lib, ya’ni bu namunada (*hk*0) va (*hk*1) kristal yo‘nalishlar shakllanganini tasdiqlaydi (6B-rasm).

Yarimo‘tkazgich namunalarni kimyoviy tarkibini o‘sish yo‘nalishida turli taqsimlanishi yoki namuna sirtini vaqt o‘tishi bilan oksidlanishi kabi holatlar ham quyosh elementi samaradorligiga ta’sir etuvchi omillardan hisoblanadi. Shu nuqtai nazardan, Sb_2Se_3 qatlamining o‘sish yo‘nalishi bo‘yicha kimyoviy tarkibining bir xilligi hamda sirtiy oksidlanish darajasi tekshirildi. Buning uchun, quyosh elementi uchun kerakli kristal strukturaga ega bo‘lgan Sb_2Se_3 namunasi tanlandi: Sb:Se nisbati 1:3 at.% ga teng manba; 2.5 Pa Ar bosimi; va 250℃ taglik harorati holatida o‘stirilgan.



8-rasm. PLD usuli bilan 300 ◦C taglik haroratida ZnO/shisha tagliklarida o‘stirilgan Sb_2Se_3 namunalarining (A) 0.4◦ burchak ostida o‘lchangan GIXRD spektri, (B) kesim yuzaning SEM tasviri va (D) kimyoviy elementlarni EDX tasviri. (C) Sb_2Se_3 namunasining optik shaffofligi (ichki tasvir: Sb_2Se_3 namunaning taqiqlangan zona kengligi). Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: intensity – signal intensivligi soni (raqamlarda); 2 theta (degree) – Rentgen nuri difraksiyasi usulida nurning namuna sirtiga nisbatan burchagi (gradusda); transmittance – namunani shaffofligi; wavelength – to‘lqin uzunligi.

8A-rasmda 0.4° burchak ostida olingan GIXRD (grazing incident XRD) spektri tasvirlangan. Koʻrsatilganidek, GIXRD spektri XRD natigasi bilan deyarli bir xil (6B-rasm). Ya'ni Sb_2O_3 choʻqqilarining yoʻqligi namuna yuzasida oksid qatlami hosil boʻlmaganligidan dalolat beradi. 8B va 8D mos ravishda Sb_2Se_3 / ZnO / SLG strukturasining kesma tasvirini va mos ravishda energodispersiyali Rentgen spektroskopiyasi (EDX) xaritasini koʻrsatadi. Bundan Sb_2Se_3 namunasini boʻshliqlarsiz va kimyoviy tarkibi gradientsiz oʻsganini koʻrishimiz mumkin. 8C-rasmda Sb_2Se_3 yupqa qatlamning optik shaffofligi va bu asosida hisoblangan taqiqlangan zona kengligi (E_g = 1.12 eV) keltirilgan boʻlib, u nazariy jihatdan hisoblangan E_g qiymatiga mos keladi. Bu implusli, lazerli oʻtkazish usulida olingan Sb_2Se_3 yupqa qatlami yaxshi optik xususiyatlarga ega ekanligini koʻrsatadi.

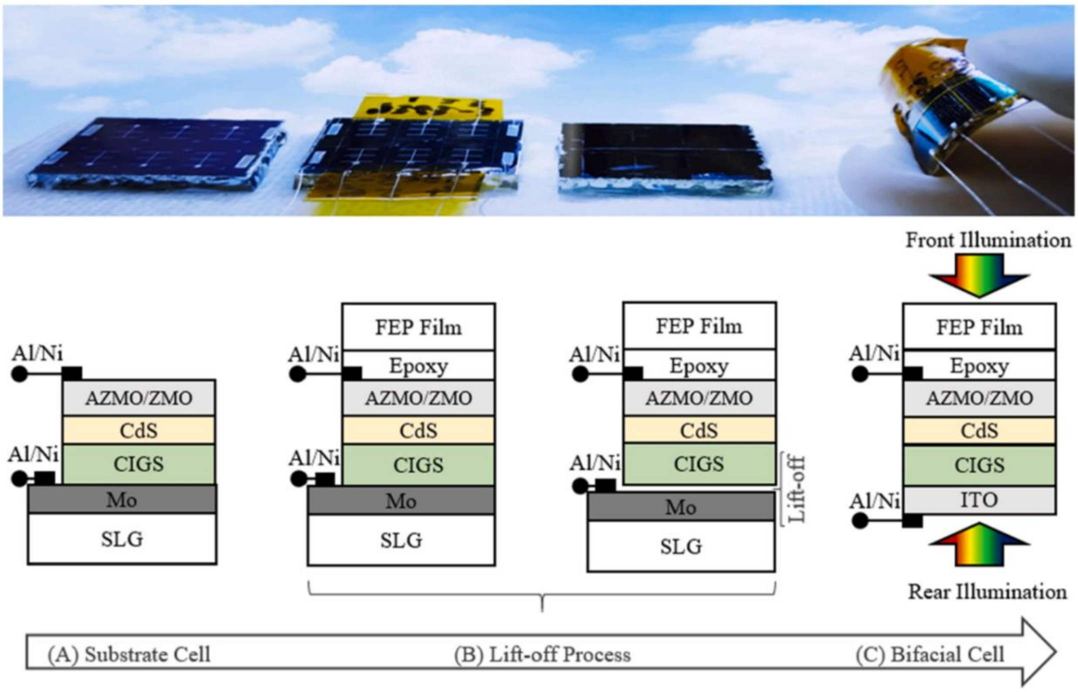
PLD usuli yordamida samarali quyosh elementi uchun foydali fizik xossalarga ega Sb_2Se_3 yupqa qatlamlari muvaffaqiyatli tayyorlandi. Se ga boy kimyoviy tarkibni qoʻshimcha selenizasiya jarayonisiz amalga oshirish mumkinligi koʻrsatildi. Bundan tashqari, avzallik kristallografik orientatsiyaga ega Sb_2Se_3 yupqa qatlam hosil boʻlishi uchun bir vaqtda PLD usulini hamma parametrlarini hisobga olish zarurligi koʻrsatildi.

II qism.

2.1. Egiluvchan, yengil va ikki yuzasidan yorugʻlik yigʻuvchi CIGS quyosh elementlarini olish

Egiluvchan, yengil vaznli va ikki yuzasidan yorugʻlik yigʻish imkoniga ega $Cu(In,Ga)Se_2$ quyosh elementlari an'anaviy (qattiq shisha tagliklarda tayyorlanadigan) quyosh elementlarga qaraganda bir qancha ustunliklarga ega boʻlib, binolarni tom va sirtini va avtomobil yuzasini qoplash kabi koʻplab qulayliklarga ega. Bundan tashqari, bu turdagi quyosh elementlari quyosh modulining taxminan 80% ogʻirligini tashkil etuvchi shisha qatlamini talab etmaydi. Qoʻshimcha ravishda, toʻgʻridan-toʻgʻri quyoshdan keluvchi nurdan tashqari, unga qoʻshimcha ravishda er sirtidan qaytgan yorugʻlik (albedo) nurlanishini ham bir vaqtning oʻzida yigʻish orqali quyosh elementlarining samaradorligini sezilarli darajada oshirish imkonini beradi. Buni ikki yuzasidan yorugʻlik yigʻish imkoniga ega quyosh elementi orqali amalga oshirish mumkin, chunki bunday quyosh elementining old va orqa yuzasidan yorugʻlik (bir vaqtda) toʻplanishi hisobiga quyosh elementining ishlash samaradorligi sezilarli darajada oshadi. Bu turdagi quyosh elementlarini tayyorlash quyidagi tartibda amalga oshirildi. 50 μm qalinlikdagi egiluvchan ftorli etilen propilen (FEP polymer substrate) polimer tagligi ustida “superstrate” strukturadagi ikki yuzasidan yorugʻlik yigʻish imkoniga ega quyosh elementini (bifacial solar cell) tayyorlandi va fizik hossalari oʻrganildi. Egiluvchan, yengil va ikki yuzasidan yorugʻlik yigʻuvchi CIGS quyosh elementlarini olish 9-rasmda koʻrsatilganidek, uch bosqichda tayyorlandi. Birinchidan, standard “substrate” tipidagi quyosh elementlari Al-Ni / $Zn_{0.9}Mg_{0.1}O$:Al (AZMO) / $Zn_{0.8}Mg_{0.2}O$ (ZMO) / CdS / CIGS / Mo / Ni-Al / SLG tuzilishida tayyorlandi (9A-rasm). 2.5 μm qalinlikdagi CIGS absorber qatlamlari Mo/SLG tagliklarida uch bosqichli bugʻlanish jarayoni (the three-stage evaporation process) usulida yuqori taglik haroratida (~550°C) oʻstirildi. Keyin, 40 nm qalinlikdagi CdS-bufer qatlami 80°C da kimyoviy vannada choʻktirish (chemical bath deposition) usulida tayyorlandi.

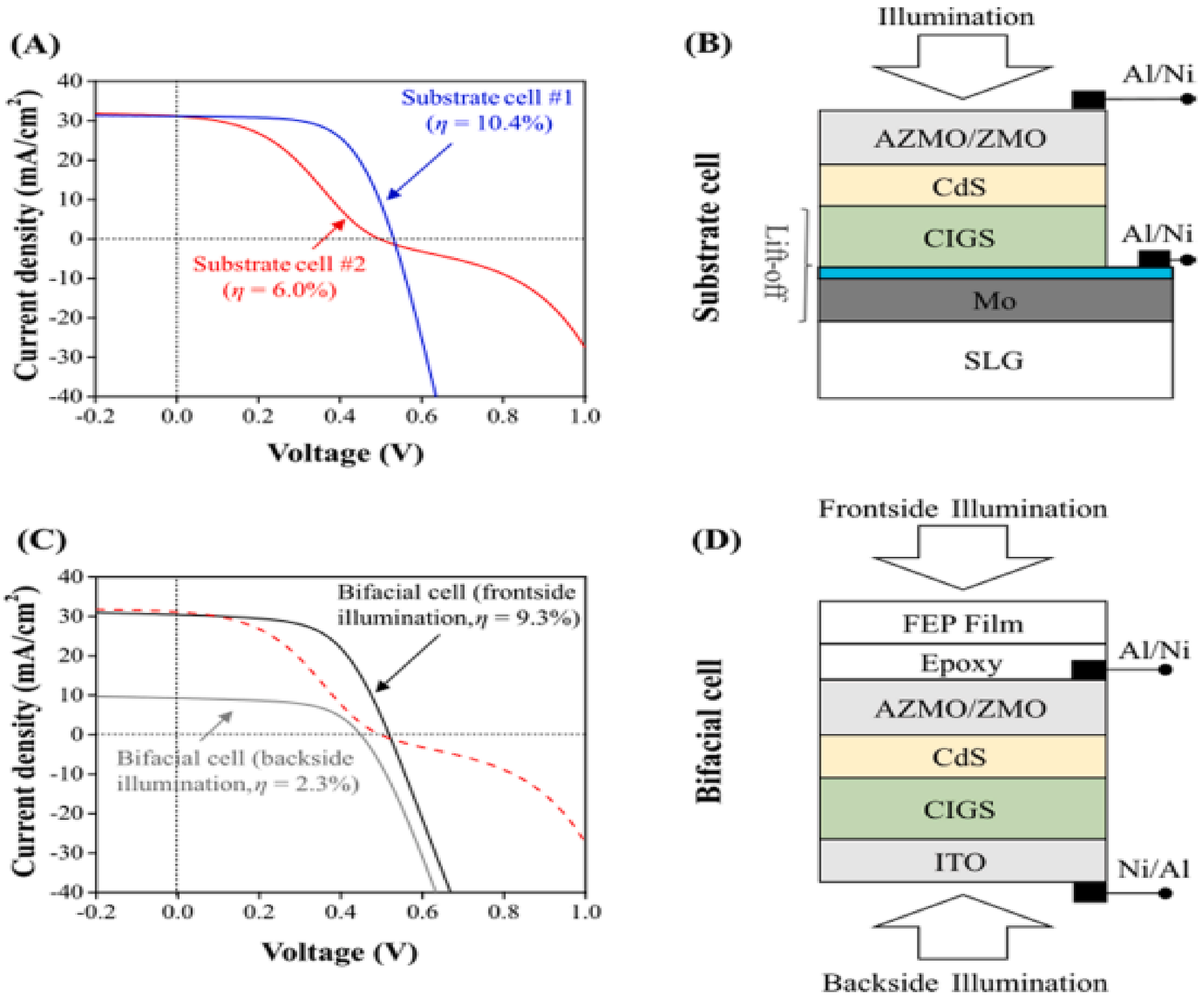
Soʻngra, ikkinchi bufer qatlam (50 nm ZnMgO (ZMO)) va shaffof elektrod (700 nm ZnMgO:Al (AZMO)) qatlamlari radiochastotali magnetron changlatish (rf magnetron sputtering) usulida xona haroratida olindi. Nihoyat, Al (1.6 μm)/Ni (100 nm) ikki qatlamli metal kontaktlari elektron dastalaridan o‘tkazish (elektron beam deposition (EB)) usulida olindi. Ushbu quyosh elementini fizik hossalari va ishlash samaradorligi o‘rganilgandan so‘ng, ikkinchi bosqichda, 50 μm qalinlikdagi FEP-polimer qatlami elektr toki o‘tkazmaydigan epoksid yelimi yordamida 100℃ haroratda quyosh elementi ustiga biriktirildi va quyosh elementini Mo/SLG tagligidan ajratish uchun ko‘tarilish jarayoni (“the lift-off process”) amalga oshirildi (9B-rasm).



9-rasm. (A) CIGS asosidagi standart strukturali quyosh elementi, (B) CIGS quyosh elementini Mo qatlamdan ajratishning “lift-off” usuli va (C) “superstrate” arxitekturasiga ega ikki yuzasidan nur yig‘ish imkoniga ega quyosh elementini sxemalari. Pastdagi strelka quyosh elementini ishlab chiqarish ketma-ketligini ko‘rsatadi. Rasmdagi foydalanilgan qisqartmalar quyidagicha: AZMO/ZMO – $Zn_{0.9}Mg_{0.1}O$:Al (2 wt.%)/$Zn_{0.8}Mg_{0.2}O$ shaffof elektrodlar; CIGS – $Cu(In,Ga)Se_2$ yutuvchi (absorber) qatlami; SLG - sodali shisha taglik; va FEP - ftorli etilen propilen polimer qatlam. Mos ravishda quyosh elementlarini haqiqiy tasvirlari yuqorida ko‘rsatilgan. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: substrate cell – Mo kontakti ustida tayyorlangan quyosh elementi; lift-off process – quyosh elementini Mo qatlamdan ajratib olish jarayoni; bifacial cell – ikki yuzadan yorug‘lik qabul qilish imkoniga ega quyosh elementi; front illumination – yorug‘likni yuqori yuzadan qabul qilish; rear illumination – yorug‘likni pastki yuzadan qabul qilish.

Nihoyat, ITO (In_2O_3:Sn) shaffof elektrodi va Al/Ni metal qatlami o‘stirish orqali yuzasi 0.23 cm^2 ga teng Al-Ni/ITO/CIGS/CdS/ZMO/AZMO/Ni-Al/Epoksid/FEP strukturali, “superstrate” tipidagi tuzilishiga ega ikki yuzasidan yorug‘lik yig‘ish imkoniga ega quyosh elementlari olindi (9C-rasm).

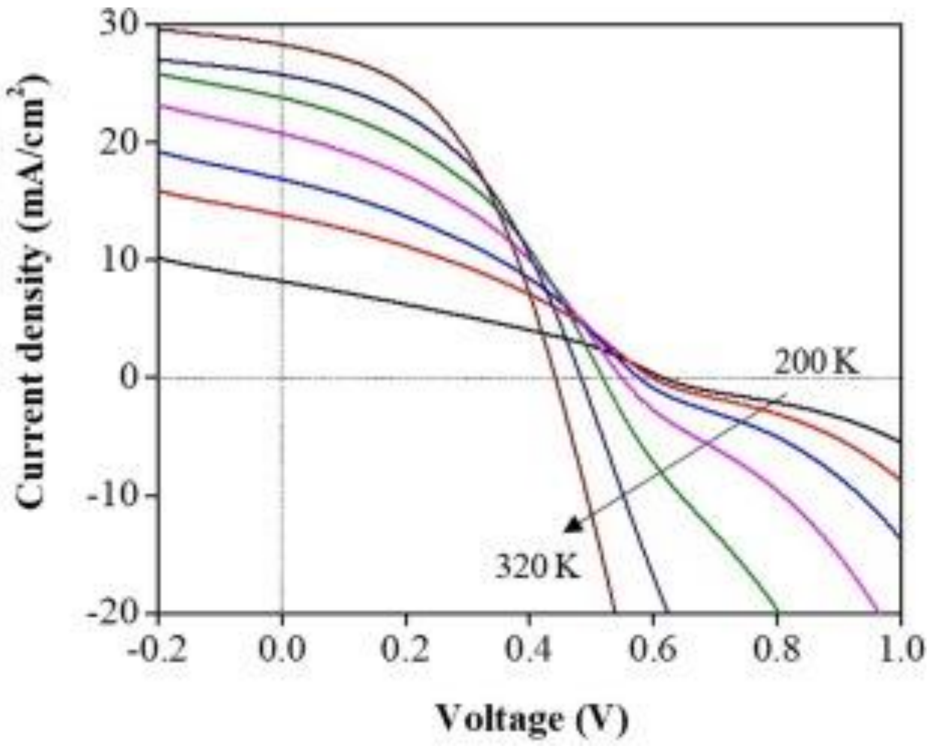
ITO qatlamning optik hususiyatlari SLG tagligida olingan ITO qatlamlarida “UV/VIS/NIR” spektrofotometr yordamida tekshirildi (Shimadzu UV-3600), elektr qarshiligi va namunalarning qalinligi mos ravishda 4 nuqtali zond usuli (NPS, JS TC-400-TF-VR) va mexanik profilometr (Dektak XT, Bruker) qurilmalarida o‘rganildi. ITO yupqa qatlamlarining kristallik sifati rentgen nurlari diffraktsiyasi (XRD) bilan o‘rganildi.



10-rasm. (A) “Standard” va (C) “bifacial” structuradagi CIGS quyosh elementlarining J-V harakteristikalari. Qurilmalarning strukturasi mos ravishda (B) Al-Ni / $Zn_{0.9}Mg_{0.1}O$:Al(AZMO) / $Zn_{0.8}Mg_{0.2}O$ (ZMO) / CdS / CIGS / Mo / SLG va (D) FEP / Epoksid / Al-Ni / AZMO / ZMO / CdS / CIGS / ITO / Ni-Al ko‘rsatilgan. (B) chizmadagi ko‘k qatlam $MoSe_2$ qatlamini ko‘rsatadi. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: current density – elektr toki zichligi; voltage – elektr kuchlanishi; substrate cell – Mo qatlami ustida tayyorlangan quyosh elementi; bifacial cell – ikki yuzadan yorig‘lik yuta oluvchi quyosh elementi; illumination – nur tushish yo‘nalishi; frontside – tepa yuza; backside – pastki yuza.

ITO yupqa qatlamlarining harakatchanligi va qarshiligi xona haroratida “Van der Pau” usuli yordamida Hall o‘lchovlari yordamida aniqlandi. Ikki yuzasidan yorug‘lik yig‘uvchi CIGS quyosh elementlarining J-V harakteristikalari va tashqi kvant samaradorligini (External Quantum Efficiency EQE) spektrlari "CEP-25RR, Bunkoukeiki" qurilmasi yordamida 25℃ da AM 1.5G (100 mW/cm^2) ostida tekshirildi.

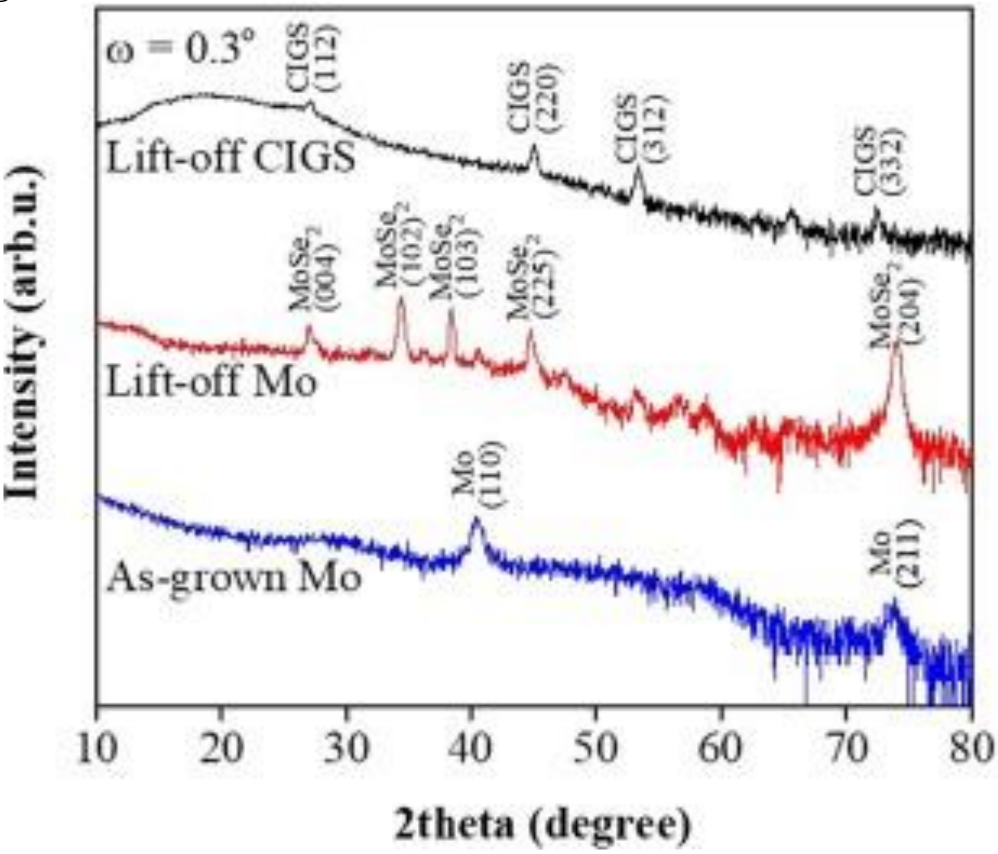
10A-rasmda bir-biriga yaqin sharoitlarda ishlab chiqarilgan ikkita standard strukturali CIGS quyosh elementlarining *J-V* xarakteristikalari ko‘rsatilgan. Bir xil qisqa tutashish toki J_{qt} (short circuit density, J_{SC}) qiymatlariga ega bo‘lishiga qaramay, ushbu quyosh elementlari turli xil to‘ldirish koeffisienti (fill factor, FF) ni va ishlash samaradorligini ko‘rsatdi. “S-shape, rollover effekt”iga ega bo‘lgan va bo‘lmagan quyosh elementlari mos ravishda 6.0% va 10.4% samaradorlikni ko‘rsatdi. CIGS va Mo orasidagi sirt chegarasini (interfeys) tadqiq qilish uchun aylanish effektiga (rollover effect) ega qurilmani quyosh elementini Mo qatlamdan ajratib olish jarayoni (lift-off) usulida ajratib olindi va ITO shaffof elektrodi va Ni/Al metal elektrodlarini o‘stirish orqali ikki yuzadan yorig‘lik yuta oluvchi quyosh elementi (bifacial cells) hosil qilindi. 10C-rasmda ko‘rsatilganidek, qurilma samaradorligi ikki yuzali quyosh elementida old yuza yoritilishi uchun 9.3% ga ko‘tarildi. Bu natija ushbu quyosh elementining “substrate” holati bilan solishtirganda sezilarli darajada yaxshilandi (6.0%, 10A-rasmdagi qizil chiziq). Bunga qo‘shimcha ravishda, orqa yuza yoritishi hisobiga 2.3% samaradorlikka erishildi. Eng muhimi, “substrate” tipidagi quyosh elementi J-V harakteristikasida kuzatilgan “rollover effect” (10C-rasmdagi kesik chiziqqa qarang), ikkala old va orqa yuza yoritilgan holatlar uchun “bifacial” quyosh elementida yo‘qoldi. “Lift-off” jarayonida “substrate” tipidagi quyosh elementining faqat orqa kontaktini o‘zgartirganligi sababli, va FEP/Epoksi/AZMO/ZMO/CdS/CIGS strukturaning old tomon tuzilishi o‘zgarmaganligi sababli (10B va 10D-rasmlarni solishtiring), J-V harakteristikalardagi holatni o‘zgarishi CIGS/Mo interfeysi bilan bog‘liqligi taxmin qilindi. Ya’ni “standard” strukturada CIGS/Mo interfeysida mavjud bo‘lgan potensial to‘siq (asosiy zaryad tashuvchi kovaklar uchun), “lift-off” jarayonidan keyin pasaygan. Ushbu potensial to‘siq balandligini baholash uchun 200-320 K harorat oralig‘ida 7.2% samaradorlikka ega “substrate” tipidagi CIGS quyosh batareyasining haroratga bog‘liq J-V xususiyatlari o‘rganildi.



11-rasm. **(**A) Al-Ni/$Zn_{0.9}Mg_{0.1}O$:Al(AZMO)/$Zn_{0.8}Mg_{0.2}O$(ZMO)/CdS/CIGS/Mo/ SLG strukturali quyosh CIGS elementining 200-320 K oralig‘ida haroratga bog‘liq J-V xususiyatlari. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: current density – elektr toki zichligi; voltage – elektr kuchlanishi.

11-rasmda 200 K dan 320 K gacha bo‘lgan haroratda “substrate” strukturadagi CIGS quyosh elementining J-V harakteristikasi tasvirlangan. Ko‘rsatilganidek, “rollover effecti” past haroratlarda ko‘proq namoyon bo‘ladi, bu esa asosiy zaryad tashuvchilar uchun kontakt to‘siqning mavjudligidan dalolat beradi. Bundan tashqari,

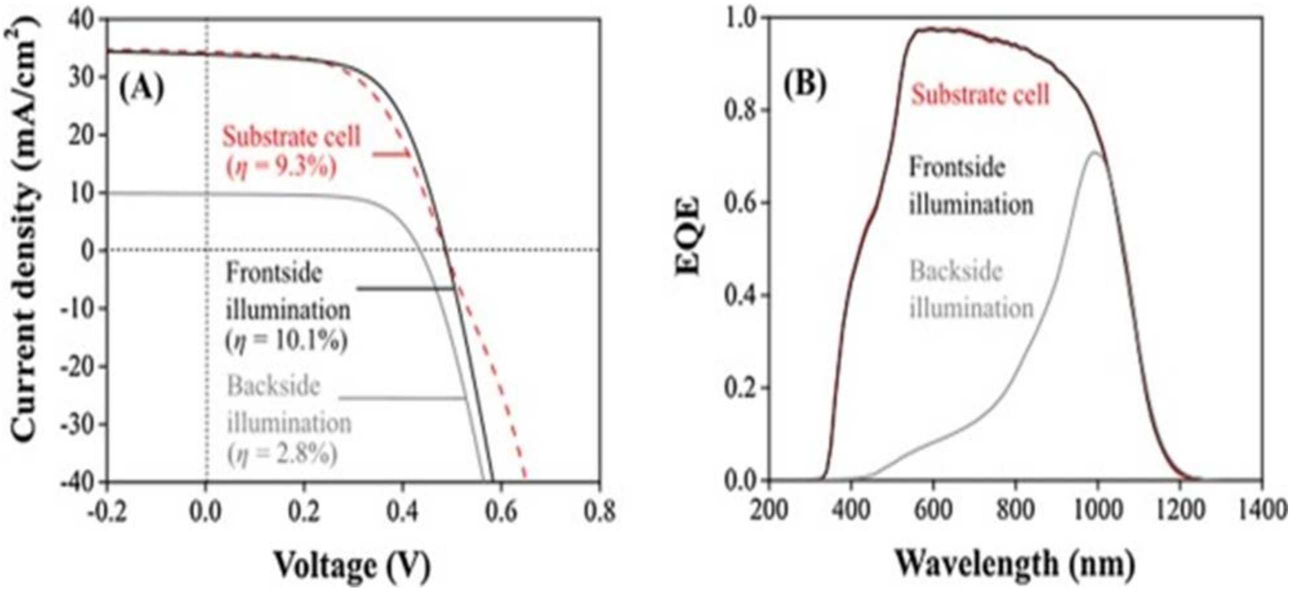
J_{qt} ham haroratning pasayishi bilan pasaygan. Adabiyotda yuqori samarali quyosh elementlari uchun J_{qt} haroratdan mustaqil bo‘lishi aytilgan. Haroratning ko‘tarilishi bilan J_{qt} dagi o‘sishi, erkin zaryad tashuvchilar uchun kontakt sohasida potensial to‘siq mavjudligini ko‘rsatdi.



12-rasm. “Lift-off” CIGS va Mo qatlamlari va yangi tayyorlangan Mo qatlami uchun tushish burchagi 0.3° bo‘lgan “Grazing-incidence X-ray diffraction” (GIXRD) spektri. Kristal strukturalar tegishli JCPDS kartalari bilan tasdiqlangan, xususan: CIGS ($CuIn_{0.5}Ga_{0.5}Se_2$, JCPDS 40–1488); “hexagonal” $MoSe_2$ (JCPDS 00-015-0029, 01-080-1179) va “cubic” Mo (JCPDS 00-001-1207). Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: intensity – signal intensivligi soni (raqamlarda); 2 theta (degree) – Rentgen nuri difraksiyasi usulida nurning namuna sirtiga nisbatan burchagi (gradusda); lift-off CIGS – Mo qatlamidan ajratib olingan GIGS namunasi; lift-off Mo – CIGS qatlamidan ajratib olingan Mo namunasi; as-grown Mo – yangi tayyorlangan Mo namunasi.

12-rasmda “lift-off” CIGS va Mo va yangi tayyorlangan Mo namunalari uchun 0.3° burchak ostida o‘lchangan GIXRD spektri ko‘rsatilgan. CIGS uchun faqat CIS (CuInS) va CGS (CuGaS) kristal strukturalar tasvirlangan. CIGS yuzasida Mo yoki $MoSe_2$ cho‘qqilarining yo‘qligi EDX ma’lumotlarini tasdiqlaydi, va “lift-off” CIGS yuzasida hech qanday Mo qatlami qolmaganidan dalolat beradi Biroq, ajratib olingan Mo namunasi yuzasida “hexagonal” $MoSe_2$ qatlamining bir nechta kristal strukturalari mavjudligi tasvirlangan, va ular Mo cho‘qqilariga nisbatan yuqori intensivlikka ega ekanini ko‘rishimiz mumkin. Bu “lift-off” Mo namunasi yuzasida $MoSe_2$ qatlami mavjudligini qo‘llab-quvvatlaydi. Adabiyotda Mo yuzasiga parallel bo‘lgan *c* koordinatasiga mos $MoSe_2$ qatlami potential to‘siq hosil qilmasligi ko‘rsatilgan. $MoSe_2$ ning (002) cho‘qqisining yo‘qligi, ya’ni 2 tetaning 13.612° holatida, $MoSe_2$

donalarining Mo yuzasiga parallel ravishda o‘sganini ko‘rsatadi, va bu CIGS/Mo interfeysida omik bo‘lmagan kontakt orqali “rollover effect”ini hosil qilgani aniqlandi.

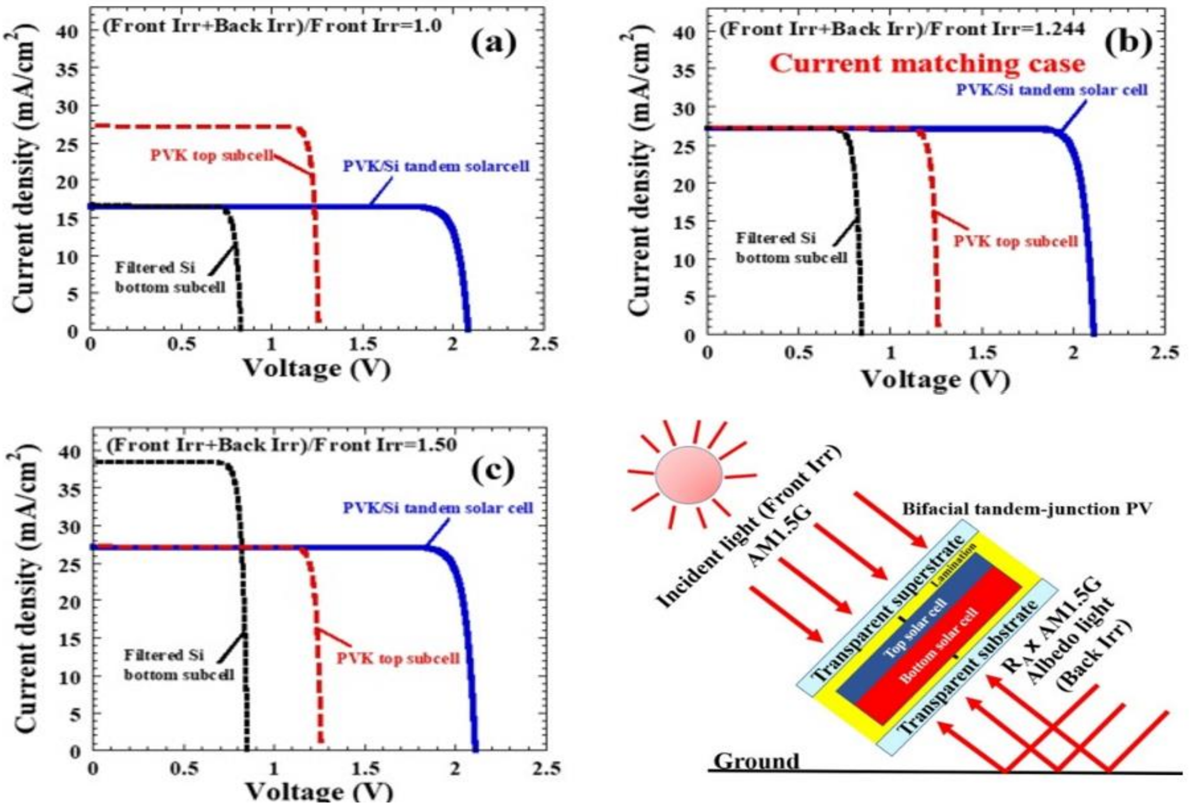


13-rasm. Al-Ni/$Zn_{0.9}Mg_{0.1}O$:Al (AZMO)/$Zn_{0.8}Mg_{0.2}O$(ZMO)/CdS/CIGS/Mo/SLG va FEP/Epoksi/Al-Ni/AZMO/ZMO/CdS/CIGS/ITO/Ni-Al. strukturali “Standard” va “bifacial” CIGS quyosh elementlarining (A) J-V harakteristikasi va (B) EQE spektrlari. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: current density – elektr toki zichligi; voltage – elektr kuchlanishi; EQE – tashqi kvant samaradorligi; wavelength – to‘lqin uzunligi

Ma’lumot uchun, $MoSe_2$ qatlamini o‘sishi, yuqori haroratda Mo ustiga CIGS qatlamini o‘stirish jarayonida tabiiy holda yuz beradi, va $MoSe_2$ ning kristal strukturasi CIGSni o‘stirish parametrlariga bog‘liq ravishda o‘zgaradi. Shunday qilib, $MoSe_2$ qatlamini optimallashtirish yoki yangi CIGS/ITO interfeysini zaryad tashuvchilar uchun omik harakterini yaxshilash zarurligi kelib chiqadi. CIGS/ITO interfeysini elektr hususiyatlarini ITO parameterlarini optimallashtirish orqali boshqarish mumkinligini ilk bor ushbu ilmiy ish doirasida ko‘rsatildi. Misol tariqasida, 13-rasmda “substrate” va “bifacial” tipidagi CIGS quyosh elementlari uchun J-V harakteristikasi va EQE spektrlari tasvirlangan. 13A-rasmda ko‘rinib turganidek, old tomondan (front) yoritish uchun “bifacial” quyosh elementning FF “rollover effect” ning kamayishi tufayli yaxshilandi. Natijada, “bifacial” quyosh elementni “front” va “rear” (orqa tomondan) yoritish holatlari uchun mos ravishda 10.1% va 2.8% samaradorlik ko‘rsatdi. “Front” yoritish natijasi “substrate” dan ko‘ra yuqori ekanini ko‘rishimiz mumkin.

Bu yuqorida muhokama qilingan CIGS/ITO interfeysida yaxshilangan omik kontakt bilan bog‘liq. Ushbu quyosh elementlari uchun qayd etilgan EQE spektrlar adabiyot natijalariga o‘xshashdir. “Rearside” yoritish uchun spektrning qisqa to‘lqin uzunligi sohasida past EQE spektrlari kuzatildi. Bu qisqa to‘lqin uzunligi ta’sirida CIGS/ITO interfeysi chegarasida hosil bo‘lgan zaryad tashuvchilar CdS/CIGS sohagacha yetib bormagani sabablidir. Ushbu sohada EQE spektrlari yaxshilash CIGS qatlami qalinligini kamaytirish va CIGS qatlamini kristal holarini yaxshilash bilan amalga oshirilishi mumkin.

2.2. Ikki yuzasidan yorug‘lik yig‘ish imkoniga ega quyosh elementlarini “tandem” strukturaga tadbig‘i



14-rasm. Ikki terminalli “bifacial” tandem quyosh elementi uchun 3 xil holatdagi J-V harakteristikalari sxematik ko‘rinishi. Old yorug‘lik AM1.5G spektridir va orqa yoritish (albedo) R_A × AM1.5G spektridir. R_A spektral mustaqillik bo‘lib, u 0 dan (bir tomonli “standard” quyosh elemennti uchun orqa yoritgichsiz) 1 gacha o‘zgaradi. Rasmdagi ingliz tilida ishlatilgan iboralarni tarjimasi: current density – elektr toki zichligi; voltage – elektr kuchlanishi; front irr – yorug‘likni yuqori yuzadan tushishi; back irr – yorug‘likni pastki yuzadan tushishi; PVK top subcell – yuqori qismdagi perovskit quyosh elementi; filtered Si bottom subcell – filterlangan pastdagi kremniy asosidagi quyosh elementi; PVK/Si tandem solarcell – PVK/Si asosidagi “tandem” (ikki qatlamli) quyosh elementi; current matching case - ikkita quyosh elementlarining elektr toki zichliklari mos kelgan holat; bifacial tandem-junction PV – ikki qatlamli va ikki yuzidan yorug‘lik yutish imkoniga ega quyosh elementi; incident light – asosiy yuzaga tushuvchi nur; albedo light – albedo nuri; ground – yer sirti

“Bifacial” ikki terminalli perovskite/kremniyli quyosh elementi qo‘shimcha R_A = 0.244 yorug‘likni “rearside” yuzadan yutilishi natijasida, “monofacial” quyosh elementidan 66% gacha ko‘proq quvvatda ishlashi aniqlandi. “Bifacial” ikki terminalli perovskite/kremniyli quyosh elementida ishlash samaradorligini keskin oshishi asosan ikkita quyosh elementi hosil qilgan J_{qt} lar orasidagi tafovutni kamaytirish hisobiga to‘g‘ri keladi. Buni 14-rasmda keltirilgan 3 xil holatdagi tandem quyosh elementlarini natijaviy J-V harakteristikalaridan ko‘rishimiz mumkin.

XULOSA

1. Sb_2Se_3 va $Cu(In,Ga)Se_2$ bo‘yicha adabiyot ma’lumotlarini tahlil qilish asosida ular asosida samarali yupqa qatlamli quyosh elementlarini yaratish imkoniyati, shuningdek ularni tayyorlash va samaradorligini oshirishning yangi fizik-texnologik usullarini izlash zarurati ko‘rsatilgan.

2. Sb_2Se_3 qatlamlarini vakuumsiz va vakuum muhitida o‘tqazish jarayonining texnologik parametrlari bilan ularning kristallfizik, morfologik, optik va elektrofizik xususiyatlari o‘rtasidagi o‘zaro bog‘liqlik o‘rnatilgan

3. Rentgen difraksiya natijalari asosida, vodorod oqimi past bo‘lganda, Sb_2Se_3 namunalari Se-boy holatda o‘sganligini, amorf strukturada bo‘lishligini va kristalchalarning (221) yo‘nalishdagi intensivligi past ekanligini, shuningdek, vodorod oqimining yuqori tezligida Sb_2Se_3 qatlamlari Sb ga boy tarkibga ega ekanligini, polikristal strukturaga ega bo‘lib o‘sishini va (211) yo‘nalishdagi intensivligi ortishini ko‘rsatdi.

4. O‘tkazilgan tajribalar asosida vakuum muhitida (211) va (221) avzal yo‘nalishlardagi yuqori sifatli polikristal Sb_2Se_3 yupqa qatlamlarni o‘stirish uchun Argon gaz bosimi 2 Pa, manba tarkibi 1: 3 at.% Sb:Se nisbatiga va taglik temperaturasi ~250°C bo‘lishligi aniqlandi.

5. ITO (In_2O_3:Sn) shaffof elektrodi va Al/Ni metal qatlamini o‘stirish usullarini takomillashtirish orqali yuzasi 0.23 cm^2 ga teng Al-Ni/ITO/CIGS/CdS/ZMO/AZMO/Ni-Al/Epoksid/FEP strukturali, “superstrate” tipidagi tuzilishiga ega ikki yuzasidan yorug‘lik yig‘ish imkoniga ega quyosh elementlari olindi. Natijada, “bifacial” quyosh elementi “front” va “rear” (orqa tomondan) yoritish holatlari uchun mos ravishda 10.1% va 2.8% samaradorlik ko‘rsatdi.

6. “Bifacial” va ikki terminalli perovskit/kremniyli quyosh elementida qo‘shimcha R_A = 0.244 (albedo) yorug‘ligi “rearside” yuzadan yutilishi natijasida, “monofacial” quyosh elementidan 66% gacha ko‘proq quvvatda ishlashi aniqlandi. Ushbu “bifacial” va ikki terminalli perovskit/kremniyli quyosh elementida ishlash samaradorligini keskin oshishi asosan ikkita quyosh elementi hosil qilingan J_{qt} lar orasidagi tafovutni kamaytirish hisobiga to‘g‘ri kelishi ko‘rsatib berildi.

SCIENTIFIC COUNCIL DSc. 02/27.02.2020.FM/T.110.01 ON AWARDING OF THE SCIENTIFIC DEGREES AT THE OF PHYSICAL-TECHNICAL INSTITUTE ACADEMY OF SCIENCES OF THE REPUBLIC OF UZBEKISTAN

PHYSICAL-TECHNICAL INSTITUTE

MAVLONOV ABDURASHID ABDUVAKHOBOVICH

OBTAINING $Cu(In,Ga)Se_2$ AND Sb_2Se_3 BASED THIN-FILM SOLAR CELLS AND INVESTIGATING THEIR PHYSICAL PROPERTIES

01.04.10-Physics of semiconductors
(physical and mathematical sciences)

PRESENTATION
ON AWARDING THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE (DSc) ON THE BASIS OF PUBLISHED PAPERS WITHOUT A DISSERTATION

Tashkent - 2024

The title of the doctoral presentation (DSc) was registered by the Supreme Attestation Commission at the Ministry of higher education, science and innovations of the Republic of Uzbekistan under number B2023.4.DSc/FM249

The work has been done at the Physical-Technical Institute of Uzbekistan Academy of Sciences.

The presentation of the work is posted in three (Uzbek, Russian, English (resume)) languages on the website of the Scientific Council at www.fti.uz and on the website of “ZiyoNet” Information and Educational Portal at www.ziyonet.uz.

Scientific consultant: **Razykov Takhir Mutalovich**
doctor of physical and mathematical sciences, professor

The defense of presentation will take place on 22 August 2024, at 10^{00} at the meeting of Scientific council DSc.02/27.02.2020.FM/T.110.01 at the Physical-technical institute Academy of Sciences of RUz. Address: Chingiz Aytmatov str 2b, 100084 Tashkent city, Uzbekistan. Conference hall of the Physical-technical Institute. Phone/fax: (+99871) 235-42-91, e-mail: ftikans@uzsci.net.

Presentation of the work is available to review in Informational-resource centre at the Physical-technical institute (is registered № 381). Address: Chingiz Aytmatov str 2b, 100084 Tashkent city, Uzbekistan. Physical-technical institute. Phone/fax: (+99871) 235-42-91.

This presentation sent out on "____" ___________ 2024 year

(Registry recond №. __ on "___" __________ 2024 year).

Kh.K. Olimov
Chairman of the Scientific Council on Award of Scientific Degrees, Doctor of Physical and Mathematical Sciences, Professor

J.S. Akhatov
Scientific Secretary of the Scientific Council on Award of Scientific Degrees, Doctor of Technical Sciences, Senior Researcher

INTRODUCTION (abstract of the DSc presentation)

Relevance and necessity of the topic. Globally, the development of ecologically clean and renewable energy sources as an alternative to current fuels (oil, natural gas, coal) has become one of the most important tasks for scientists in the field. These efforts are based on protecting Earth's biosystems by reducing air pollution caused by the massive consumption of oil, coal, and natural gas. In practice, the replacement of existing energy technologies with a new type of alternative is carried out step by step. In this context, the analysis of the use of energy resources is called "energy structure of the 21st century" as a "period of best MIX age" that includes various forms of renewable energy. Photovoltaic technologies, i.e. obtaining electricity directly from sunlight on the basis of solar cells, has become one of the most promising projects among the development projects of environmentally friendly energy production technologies. This technology makes it possible to produce electricity without noise and without pollution like smoke. By choosing the size of the photovoltaic cell, this technology can produce electricity in the milliwatt (mW) to megawatt (MW) range.

Worldwide, although in the early period (1950-70s), the practical use of solar cells was limited to space projects to provide electricity to earth satellites. Because the cost of solar cells is several thousand times more expensive than today's cost, the great attention paid to the field in this early period has served as a foundation for today's achievements. We can now see solar cells in various geographic locations, deserts, building roofs and exteriors, vehicles, and even lake and sea surfaces ("floating PV"). As a result of continuous scientific research, the efficiency of solar cells is increasing, and the scale of production is increasing day by day. However, further reducing the cost of PV modules is one of the top priorities today in this field. On this front, extensive research and development has been carried out in recent decades at all technical stages, from the raw materials required for solar cells to industrial-scale production processes. Consequently, the cost of photovoltaic technologies has fallen significantly, resulting in the cost of solar cell-based electricity approaching that of current conventional alternatives. Costs need to be further reduced to make this technology more competitive. Currently, polycrystalline and monocrystalline silicon-based photovoltaic systems account for >90% of the solar energy market share, with the remaining <10% coming from new types of thin-film technologies such as CdTe and $Cu(In,Ga)Se_2$. The efficiency of these technologies reached >22% at the laboratory scale and approached 20% at the module level. Note that these figures are obtained for single junction solar cells. In order to achieve further cost reduction, it is necessary to find solutions to several scientific problems. Production of solar cells with two or more absorbing layers based on photovoltaic technologies (tandem structure) or research and development of effective solar cells based on inexpensive chemical cells widely available on earth are promising strategies.

In our country, more and more attention is being paid to fundamental and applied research for the development of current and priority areas of science and technology in recent years. In particular, the development of theoretical and practical physical research, which is one of the promising directions, is an important issue today. The main directions of fundamental research and development for the successful development of science in our country and their practical application are reflected in the Strategy for further development of the Republic of Uzbekistan in 2022-2026. Therefore, the study of solar elements with high efficiency remains one of the urgent issues in the field of fundamental and applied research.

This scientific research work corresponds to the tasks defined by the following state regulatory documents: PF-4947-Decree of the President of the Republic of Uzbekistan dated February 7, 2017 on measures for "strategies to further develop the Republic of Uzbekistan, and No. PQ-2789-Decree of the President of the Republic of Uzbekistan dated February 18, 2017 measures “to further improve the activities of the Academy of Sciences, developinging its organizational, financing, and research activities" and others.

Compliance of the research with the main priorities of the development of science and technology of the Republic of Uzbekistan. Dissertation research was conducted in accordance with the priority directions of science and technology of the Republic of Uzbekistan: II. "Conserving power, energy and resources".

Review of overseas scientific investigations on the topic of the presentation[1]. Scientific investigations on the study of physical and technological properties of solar cells and semiconductor materials necessary for their preparation have been carried out by the world's leading universities and scientific centers, including the universities of Halle, Leipzig, Magdeburg (Germany), "National Renewable Energy Laboratory", "Colorado State University" (USA), Swiss Federal Laboratories for Materials Science and Technology (EMPA), Parma, Verona universities (Italy), "University of New South Wales" (Australia), "University of Electronic Science and Technology of China" (China), Kyoto and Ritsumeikan universities (Japan). Scientific investigations in this field have been constantly carried out not only in universities, but also by factories producing such solar cell modules. For example, First Solar (USA), Oxford PV (Great Britain), CTF Solar, AVANCIS, QCELLs (Germany), Solar Frontier, Panasonic, Sekisui (Japan) can be cited.

The degree of knowledge of the problem. Scientific research on the development of efficient solar cells has been studied by various researchers around the world. In particular, based on Si - M. Green (Australia); based on Cu(In,Ga)Se_2 - A. Tiwari (Switherland), R. Scheer (Germany) and T. Minemoto (Japan); and based on Sb_2Se_3 - J. Tang (China).

For more than 60 years, work has been carried out on solar cells based on aforementioned materials and other materials.

It has been proved that it is possible to practically prepare solar cells with high efficiency. Today's scientific problems in this field include the further reduction of the cost of solar cells, the improvement of their efficiency, and the preparation of different colors, light, and flexible substrates.

Under the leadership of M.S. Tivanov, Dean of the Physics Department at the Belarusian National University, scientific researches are conducted to obtain thin-film solar cells. Under the leadership of T.M. Razikov, head of the laboratory at the

[1] Review of foreign scientific research on the topic of the presentation https://scholar.google.com/, https:// www.linkedin.com/, https://www.dgfi.unsw.edu.au/, https:/ /www.empa.ch/web/s207, https://www. Developed from physik.uni-halle.de/fachgruppen/photovoltaik/, https://www.ritsumei.ac.jp and other sources.

Physical- Technical Institute, scientists from Uzbekistan have developed a new technology called chemical molecular beam deposition for obtaining solar cells from two- and multi-component chalcogenide semiconductors.

However, until now, the preparation of solar cells based on the binary compound Sb_2Se_3 and $Cu(In,Ga)Se_2$ using the chemical molecular beam deposition method has not been studied. Therefore, studying the conditions for obtaining Sb_2Se_3- and $Cu(In,Ga)Se_2$-based solar cells, and the establishment of laws of dependence on the electrical and optical properties of solar cells obtained by the recommended method in this presentation are carried out, which is of great interest for both science of semiconductor physics and practice in semiconductor materials and devices.

Connection of the topic of the dissertation topic to the scientific works of higher education and research institutions, where the dissertation is carried out.

Scientific works based on Sb_2Se_3 funded by the Academy of Sciences of the Republic of Uzbekistan "Complex research and development of thin-layer solar cells based on new types of chalcogen materials" (2021-2024). The scientific work based on Cu(In,Ga)Se2 has been shown interest and funded by Japanese companies such as "Solar Frontier" and "Toshiba".

The purpose of the study. Obtaining and physical properties of thin-film solar cells based on $Cu(In,Ga)Se_2$ and Sb_2Se_3.

Research tasks: Obtaining thin layers of Sb_2Se_3 in vacuum and non-vacuum environments;

Study of surface and structural properties of Sb_2Se_3 thin layers obtained in vacuum environments;

Development of physical and structural properties of Sb_2Se_3 thin layers obtained in non-vacuum environments suitable for use in solar cells;

Production of $Cu(In,Ga)Se_2$ based thin film solar cells based on "standard" structure;

Preparation and performance study of bifacial solar cells based on $Cu(In,Ga)Se_2$ thin layer solar cells obtained in the "standard" structure;

Theoretical analysis of the effectiveness of applying $Cu(In,Ga)Se_2$ thin film solar cells obtained in the "bifacial" structure to "tandem" (multilayer) solar cells.

The object of research is thin-film solar cells based on $Cu(In,Ga)Se_2$ and Sb_2Se_3, obtained using chemical molecular beam deposition and pulsed-laser deposition (PLD) methods.

The subject of the research is obtaining Sb_2Se_3 thin layers in vacuum and non-vacuum environments, preparing $Cu(In,Ga)Se_2$ thin layer solar cells in "standard" and "bifacial" structures, analyzing the performance of solar cells with a "bifacial tandem" structure using numerical models.

The research method. Obtaining semiconductor thin layers and solar cells in devices operating in vacuum and non-vacuum environments, X-ray diffraction method for studying the structural properties of obtained thin layers, atomic force microscopy and scanning electron microscopy for determining the surface morphology of layers, determining the mobility of charge carriers by Hall effect method, modern photovoltage methods for measuring optical properties, analysis of current-voltage characteristics for determining current transfer mechanisms, modern ellipsometry methods for determining the limit of optical light absorption, and several other modern methods were used.

The scientific novelty of the research is as follows:

for the first time, the relationship between the physical properties of Sb_2Se_3 thin films obtained in vacuum and non-vacuum environments has been studied. It was found that Sb_2Se_3 films deposited at substrate temperatures of T ≥ 300°C with a polycrystalline structure (hkl, λ ≠ 0) grow perpendicular to the substrate surface in the crystal direction and are stoichiometrically rich in Se. These films exhibited chemical distribution on the surface, a bandgap (Eg) of 1.12 eV, and resistivity ranging from 10^4 to 10^6 Ohm x cm;

Sb_2Se_3 films obtained from sources with Sb:Se atomic ratios of 2:3 and 1:4 in a vacuum environment at a temperature of T = 250°C and Argon gas pressure of 2-3 Pa not only showed (hkl, l ≠ 0) but also (hkl, l = 0) peaks with relatively high intensity. Additionally, Sb_2Se_3 films obtained from a source with an Sb:Se atomic ratio of 1:3 demonstrated that (hkl, l ≠ 0) peaks grew perpendicular to the substrate surface in the crystal direction, as determined by X-ray structural analysis;

energy dispersive X-ray spectroscopy revealed that obtaining Sb_2Se_3 thin films in a vacuum environment at temperatures higher than 300°C leads to the reduction of the Se element in the sample;

based on the results of X-ray diffraction, scanning electron microscopy, the Hall method, and ellipsometry methods, the optimal technological modes for preparing Sb_2Se_3 thin films in a non-vacuum environment were determined, in accordance with the requirements for efficient solar cells;

for the first time, the possibility of performance enhancement was proved via lift-off method to convert the standard-type $Cu(In,Ga)Se_2$-based thin film solar cells to the bifacial-type;

for the first time, the possibility of performance enhancement up 62% was shown by using a bifacial solar cell in a tandem structure via significantly reduced energy losses.

The practical results of the research are as follows:

physical and technological aspects for the preparation of Sb_2Se_3 thin films in vacuum environment at temperature below 300°C with desired physical properties for efficient solar cells was developed;

the degree of surface oxidation on Sb_2Se_3 thin films, i.e., deposited in a vacuum environment, was studied. High resistance of Sb_2Se_3 thin films for surface oxidation (no formation of oxide layer) has been shown on the basis of specific experiments;

based on the analysis of experimental data, performance enhancement of thin film solar cells was shown based on bifacial $Cu(In,Ga)Se_2$ solar cells, which can receive sunlight from two (upper and lower) surfaces. This led to the absorption of more sunlight and increased solar cell efficiency;

the physical and technological basis of obtaining bifacial $Cu(In,Ga)Se_2$-based thin-film solar cells was developed;

fabrication possibility of bifacial $Cu(In,Ga)Se_2$-based thin-film solar cells on a lightweight and flexible polymer substrate was shown;

physical-technological basis for the controlling the physical properties of $MoSe_2$ that formed between Mo metal substrate and $Cu(In,Ga)Se_2$ layers was shown. By eliminating the energy losses at the $Cu(In,Ga)Se_2$/Mo interface, an increase in the performance of the $Cu(In,Ga)Se_2$-based thin film solar cells was achieved.

The reliability of the research results was ensured by the use of modern proven methods of mathematical physics, computational mathematics and semiconductor physics. The samples were taken on the basis of technologies widely used in the preparation of semiconductor materials. The results are strictly analyzed within the framework of the mathematical apparatus of general classical and quantum physics. Modern numerical and analytical methods of calculation were also used, and the results were compared with the available data and the results of other authors. The conclusions of the work correspond to the basic rules of the physics of solar cells and semiconductors.

The scientific and practical significance of the research results. The scientific significance of the research results is that it is possible to form efficient solar cells based on new semiconductor elements or compounds. In addition, further improvement of existing solar cells - making them capable of receiving sunlight bifacially will help to increase their efficiency even more.

The practical importance of the research results is that they will contribute for the further development of ecologically friendly, low-cost, and highly efficient thin-film solar cells in a large scale.

Implementation of research results.

The scientific results on the development of $Cu(In,Ga)Se_2$ and Sb_2Se_3-based samples and thin-film solar cells have been used in the works of foreign researchers, in particular to explain the physical properties of solar cells based on these samples and increase their efficiency. The list of citations given to these scientific works in the "Web of Science" and "Scopus" databases are more than 1000 (as of October 2023), some of which are listed below:

The products obtained from studying the morphological, structural, and optical-electrical properties of different film compositions serve to optimize the parameters of the Sb_2Se_3 film. Relevant researches have been published in journals such as (Solar Energy Materials and Solar Cells. Impact Factor: 7,267. Vol. 200, 15 September 2019, 109945; Solar Energy, Impact Factor: 5,95. Vol. 187, 15 July 2019, Pages 404-410; Solar Energy, Impact Factor: 5,95. Vol. 188, August 2019, Pages 586-592). These studies focus on the use of antimony selenide and the electrical and optical properties of solar cells based on these materials. Further refinement in the scientific and technological processes has led to the creation of a thin-film solar cell with an efficiency of 5.6%.

The presence of contact resistance and electric potential observed on the surface of $Cu(In,Ga)Se_2$/ITO made it possible to explain these scientific problems in solar cells based on other types of semiconductor materials. In particular, it was used to develop the Sb_2Se_3/Fe_2O_4(FeS) surfaces (Solar Energy, Impact Factor: 6,7. Vol. 249, 1 January 2023, Pages 414-423). In addition, it has been used in the development of solar cells based on $Cu(In,Ga)Se_2$/ITO with semi-transparent optical properties with improved stability (Solar RRL, Impact Factor: 8,31. Vol. 6, 17 February

2022, 2101071).Moreover, it was used to improve the efficiency of solar cells based on p-type CZTSSe (Journal of Materials Science: Materials in Electronics, Impact Factor: 2,48. Vol. 32, 7 August 2021, Pages 22535-22547).This concept has also been adopted into wide-gap chalcopyrite solar cells to demonstrate the feasibility of ITO material (Solar RRL, Impact Factor: 8,31. Vol. 6, 18 May 2022, 2200401). Most importantly, it was found that an efficient solar cell can also be obtained using a chemically prepared $Cu(In,Ga)(S,Se)_2$ on ITO surface (Advanced Materials Interfaces, Impact Factor: 6,39. Vol. 10, 1 September 2023, 2300566).

Our scientific research findings on the formation of $MoSe_2$ layer at the $Cu(In,Ga)Se_2$/Mo interface was used to increase the V_{oc} of the solar cell by 100 mV, reduce the capacitance resistance formed on the back surface, and prepare efficient solar cells at low temperatures (Nature Energy, Impact Factor: 27,05. Vol. 8, 21 November 2022, Pages 40-51; Advanced Functional Materials, Impact Factor: 19,41. Vol. 33, 20 July 2023, 2303188; Progress in Photovoltaics: Research and Applications, Impact Factor: 8,05. Vol. 30, 21 October 2021, Pages 191-202).This concept has also been used in Sb_2S_3 solar cells to use a Mo substrate (Advanced Science, Impact Factor: 17,52. Vol. 10, 5 September 2023, 2303414).

Publication of research results. The results of DSc research are reflected in more than 35 scientific articles published in prestigious Q1/Q2 type scientific journals recommended by the Higher Attestation Commission under the Ministry of Higher Education, Science and Innovation of the Republic of Uzbekistan.

THE MAIN CONTENT OF THE WORK

Part I.

Antimony selenide (Sb_2Se_3) is a semiconductor compound belonging to the family of inorganic V_2-VI_3 compounds (Bi_2S_3, Bi_2Se_3, Bi_2Te_3, Sb_2S_3, Sb_2Se_3, Sb_2Te_3). Sb_2Se_3 compounds occur naturally as the mineral stibnite and have an orthorhombic structure formed by $(Sb_4Se_6)_n$ bands aligned parallel to the [001] direction. Despite the fact that these materials have a similar structure, only a few of them, such as Sb_2S_3, Bi_2S_3 and Sb_2Se_3, can be used for solar cells. In general, theoretical calculations showed that solar cells based on Sb_2Se_3 have the highest potential among V_2-VI_3 compounds.

Sb_2Se_3 has attracted considerable interest from scientists in the field as a useful compound for use in solar cell, battery, and photochemical applications. The abundance of elements Sb and Se in the earth's crust is 0.2 and 0.05 ppm, respectively, and Sb_2Se_3 has good physical and chemical stability. Figure 1 shows recent research achievements as well as future research directions for Sb_2Se_3-based thin-film solar cells. As shown in Figure 1, to improve the efficiency of the solar cell, it is required to reduce the (221) crystal orientation and the defect density.

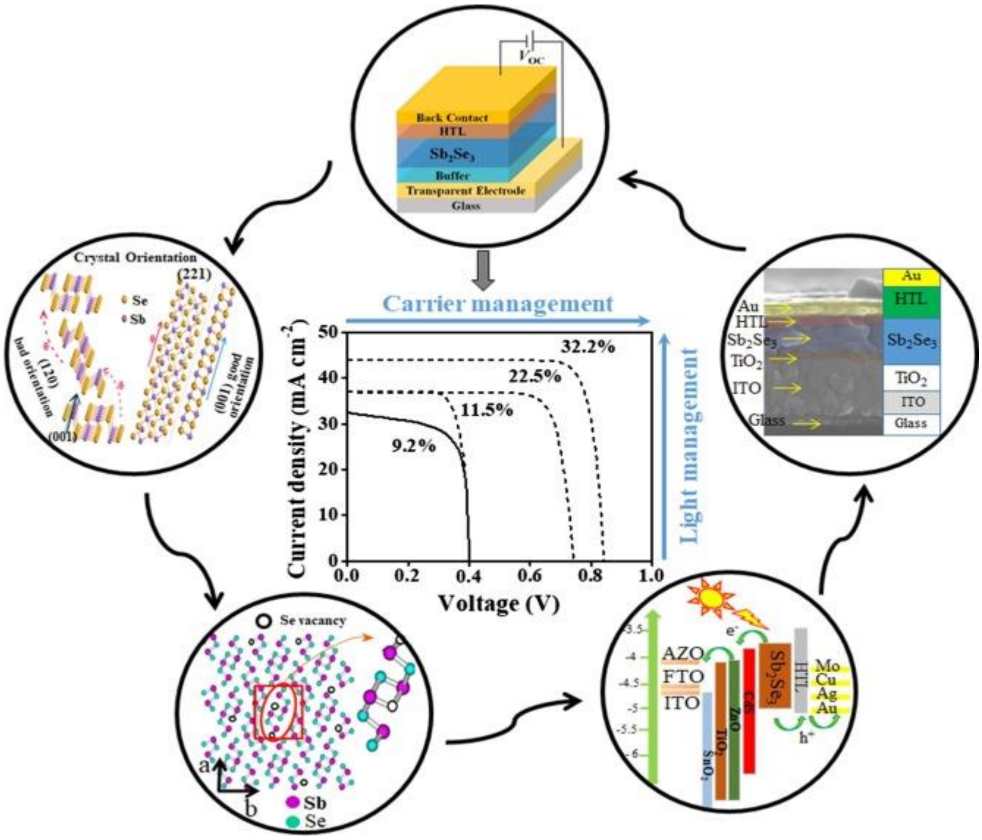


Fig. 1. Main research areas on the Sb_2Se_3-based solar cells**.**

Among the defects, reduction of Se vacancies (V_{Se}) is important. In general, Sb_2Se_3 is gaining interest in the research of this compound in the scientific community due to its favorable material properties and increased performance in fast photons. More than 200 papers on Sb_2Se_3- and relative materials based solar cells have been published in the past decade (Fig. 2).

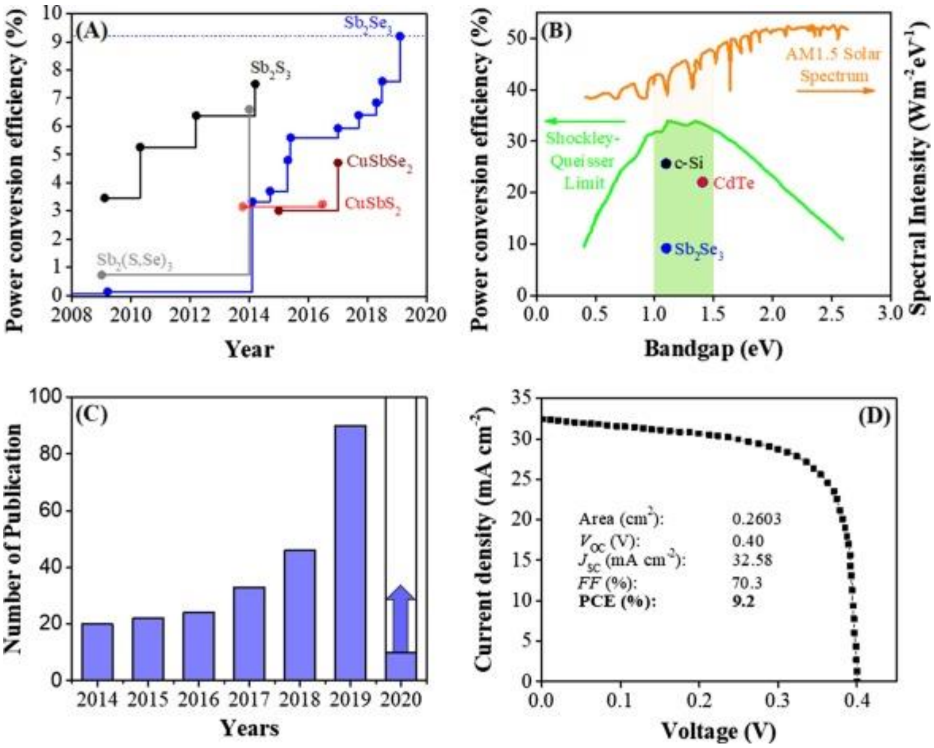


Fig. 2. Performance and number of published articles on Sb_2Se_3 and Sb_2S_3-based solar cells are listed.

1.1. Crystal structure and physical properties of Sb_2Se_3

Sb_2Se_3 crystallizes in the orthorhombic structure (Fig. 1) belonging to the Pnma (62) crystal group. Crystal structure parameters of Sb_2Se_3 have been calculated and measured by several research groups. Sb_2Se_3 crystal lattice dimensions are a = 11.62 ± 0.01 Å, b = 3.962 ± 0.007 Å and c = 11.77 ± 0.01 Å, and the smallest cell size is 0.524 nm^{-3}. The "bonded" Sb-Se distances range from 2.576 Å to 2.777 Å, while the "unbonded" Sb-Se distances start at 2.98 Å. The Se-Sb-Se and Sb-Se-Sb angles are 86.6° and 96.0° and 91.0° and 98.9°, respectively.

The Sb_2Se_3 structure consists of Se-Sb-Se chains along the c axis. That is, the Sb_2Se_3 crystal has a crystal structure consisting of one-dimensional (1D) ribbons formed from Sb_4Se_6 units, these ribbons are interconnected by weak Se-Se interactions. Stereochemically active Sb s^2 bonds lead to square pyramidal coordination around Sb; Thus, it occupies the space between the tapes. In general, the 1D crystal topology is one of the main advantages of Sb_2Se_3 for high efficiency solar cell. In other words, the bonds between the 1D ribbons formed by Sb_4Se_6 units are weaker than the bonds within the ribbons, which is the main reason for the anisotropic nature of the electron movement. Due to the 1D structure, grain boundaries parallel to the ribbons are naturally good for reducing the recombination of charge carriers (free electrons).

This is especially true in polycrystalline structured solar cells with three-dimensional (3D) bonding. Studies conducted on theoretical calculations (Density Functional Theory) have shown that the boundaries of Sb_2Se_3 grains, where the electron density is collected in ribbons, are good electrical conductors. The (001) orthogonal surfaces of the crystal, such as (010), (110) and (120) surfaces, have been calculated to have the lowest surface energies. Furthermore, the average surface potential of Sb_2Se_3 films was found to be 9.1 mV, which is significantly lower than that of CIGS or CZTS (>100 mV). Thus, in Sb_2Se_3, the recombination loss with defects in Sb_2Se_3 can be minimized if the surfaces are terminated with properly oriented $[Sb_4Se_6]_n$ ribbons. In 3D polycrystalline thin-film solar cells, recombination of charge carriers can be reduced by passivation. In comparison, in Sb_2Se_3, such passivation is not required, but by controlling the orientation of the film, due to its anisotropic properties, it is one of the key factors in achieving a high-efficiency solar cell.

As mentioned above, the 1D anisotropic structure of Sb_2Se_3 gives rise to efficient electric charge transport properties.

In general, Sb_2Se_3 has *p*-type electrical conductivity - suitable for a solar cell. However, some Sb_2Se_3 samples show *n*-type conductivity with external dopants such as Te, Bi. In addition, specific defects of Sb_2Se_3, such as selenium vacancy (V_{Se}), also form an n-type defect, that is, it has electron-donating properties. Since *p*-type Sb_2Se_3 is used for solar cells, it is desirable to prepare samples in *p*-type.

The photosensitivity of Sb_2Se_3 samples in dark and illuminated conductivity values were 2×10^{-8} and 1×10^{-6} $(\Omega\ cm)^{-1}$, respectively. Charge carriers (positively charged holes) have been found to have a mobility of 22 $cm^2V^{-1}s^{-1}$, which is higher than CZTS (10 $cm^2V^{-1}s^{-1}$) or PbSe (<1 $cm^2V^{-1}s^{-1}$). Nevertheless, 1D crystal grain orientation is important to increase the efficiency of solar cells by maintaining maximum mobility and minimum recombination. At the same time, the density of free charge carriers for efficient solar cells is lower than the optimal value of ~ 10^{13} cm^{-3} to 10^{16} cm^{-3}, and it is desirable to increase the density of free charge carriers in Sb_2Se_3.

In the initial work on Sb_2Se_3, it was determined that the activation energy (Ea) of Sb_2Se_3 crystals varies in a wide energy range (0.2-1.0 eV). This change was found to be in the range of 0.54-0.66 eV depending on the difference in the Fermi level attached to another position in the energy gap or the thickness in the Sb_2Se_3 samples. The activation energy was also found to be related to the chemical composition, and it was found that Ea decreased from 1.0 eV to 0.2 eV when the value of x was from 0.0 to 0.9 in Sb_xSe_{1-x} samples.

The reported high activation energy indicates the existence of deep defect energy levels. Taking these into account, the main defect density in the grown Sb_2Se_3 films was found to be about 10^{14} cm^{-3}, which is higher than that of CdTe-based solar cells (from 10^{11} to 10^{13} cm^{-3}). In summary, reducing the density of these deep-level defects is required to increase V_{OC} and improve solar cell efficiency.

1.2. Growing Sb_2Se_3 samples without vacuum Growing Sb_2Se_3 samples in a vacuum environment is one of the effective ways to reduce the cost of solar cells. In this context, Sb_2Se_3 samples were obtained for the first time by the "chemical molecular beam deposition" (CMBD) method. The physical properties listed above, necessary for obtaining an efficient solar cell, were studied. That is, the morphological and structural characteristics of Sb_2Se_3 samples were studied and ways of their effective management were determined.

For this purpose, Sb_2Se_3 samples were systematically studied at different stage substrate temperatures as a function of carrier gas (hydrogen) flow rate. Experimental data have shown that when the hydrogen flow is low, Sb_2Se_3 samples grow in a Se-rich state and the samples are mostly in amorphous structure. However, in this case, the crystal structure of Sb_2Se_3 samples showed small (221) peaks.

In contrast, at high hydrogen flow rates, it was observed that the films grow with Sb-rich content and polycrystalline structure, and the intensity of (211) signals increases (Fig.3). The growth of the samples in the Sb-rich condition is related to the high substrate temperature, which can be explained by the re-evaporation of Se from the sample (Fig.4).

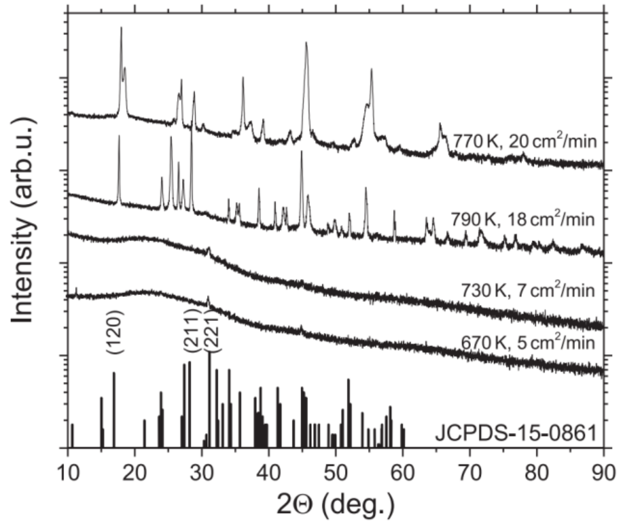


Fig. 3. X-ray diffraction data of Sb_2Se_3 films grown at different hydrogen flow rates at fixed substrate temperatures without vacuum

Electrical and optical properties of polycrystalline Sb_2Se_3 samples were found to have p-type conductivity and high absorption coefficient (10^5 cm^{-1}) and optical band gap of 1.1 eV. These experimental results are consistent with the physical properties of vacuum-grown Sb_2Se_3 samples, and are suitable for thin-film solar cells.

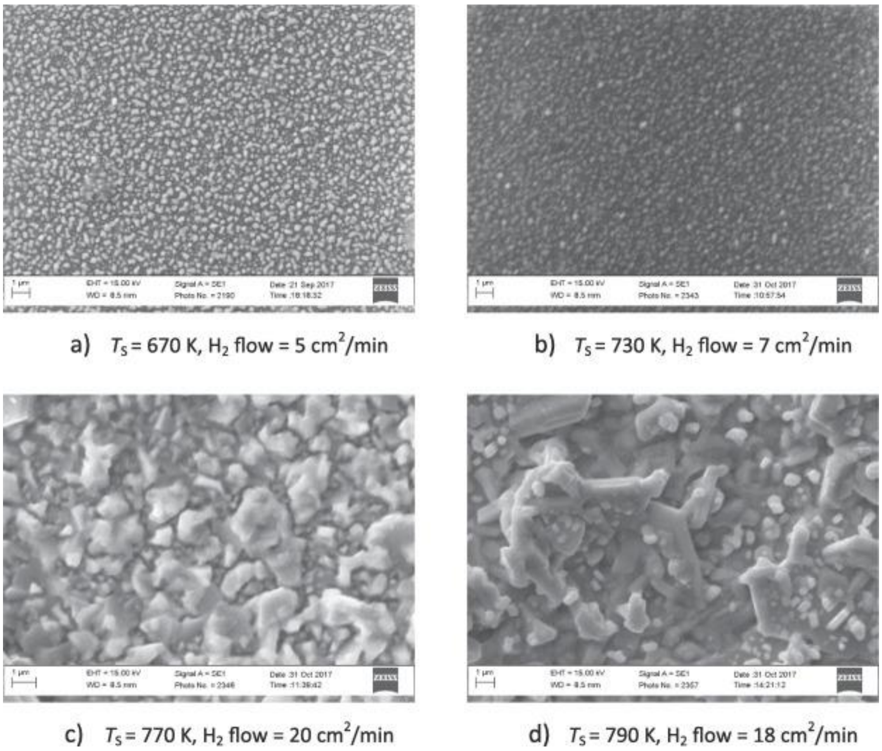


Fig. 4. (a, b) SEM images of Sb_2Se_3 samples grown at low hydrogen flow rates (5-7) cm^2/min and (c, d) at high hydrogen flow rates (18-20) cm^2/min. Images were recorded at an acceleration voltage of 15 kV with a working distance of 8.5 mm.

1.3. Growing Sb_2Se_3 samples in a vacuum environment

Figure 5A depicts the XRD spectrum of Sb_2Se_3 thin layers grown by pulsed-laser deposition (PLD) under vacuum conditions at different substrate temperatures. As shown, samples grown at low temperature (up to 175°C) have an amorphous structure. At higher substrate temperatures (250°C), the samples grow in a polycrystalline structure, meaning that all XRD diffraction peaks are indexed to the orthorhombic phase of Sb_2Se_3 (JCPDF #15-0681). However, this sample showed not only useful peaks for the solar cell, i.e. (hkl, $l \neq 0$), but also useless (hkl, $l = 0$) peaks. For substrate temperatures in the range of 300-400°C, samples were found to grow with predominantly unfavorable (hkl, $\lambda = 0$) peaks, regardless of the target chemical composition. In addition, Sb_2Se_3 thin films grown at substrate temperatures above 300°C have a low chemical composition relative to the stoichiometric ratio, which may be due to re-evaporation of Se element from the sample. This resulted in contamination of the vacuum chamber (inside the PLD chamber) and a coating of Se film on the "entry window" of the chamber.

Thus, it was confirmed that it is necessary to grow Sb_2Se_3 thin films under vacuum conditions at a substrate temperature below 300°C. Figure 5B shows the XRD spectrum of Sb_2Se_3 films obtained at different Ar gas pressures. Despite the fact that a clear transition from the amorphous phase to the polycrystalline phase was observed, the intensity increase was mainly observed in the "unwanted" (hkl, $\lambda = 0$) crystal directions, which is significant for (230). In the literature, this pattern was associated with high temperature. Yuan et al. found that increasing the annealing temperature in the range of 320–440°C mainly increases the intensity of (110), (020),

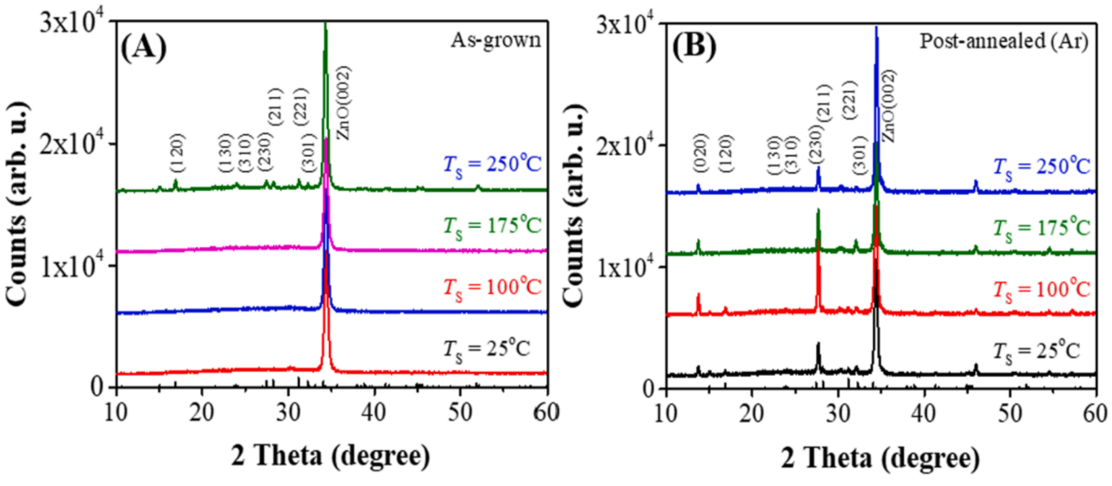


Fig. 5. XRD spectrum of (A) Sb_2Se_3 samples grown at the specified substrate temperature by the PLD method, and (B) heated at 400°C for 5 minutes in an Ar atmosphere using a rapid thermal annealing system.

(120), (230), and (240). Lee et al. also confirmed the growth of Sb_2Se_3 films in crystal directions with (hkl, $\lambda = 0$) at a temperature of 330°C. It should be avoided because (hkl, l=0) crystal orientations, in particular (120) cause an increase in the electrical resistance of solar cells. The same results were obtained under N_2 gas pressure as Ar gas. Since the above experiments were not enough to improve the crystal orientation, especially because the Sb_2Se_3 films grown at lower substrate temperatures grew in an amorphous structure, these samples were then annealed at 250°C under different Ar pressures for a short time (5min. “rapid thermal annealing" method) was heated.

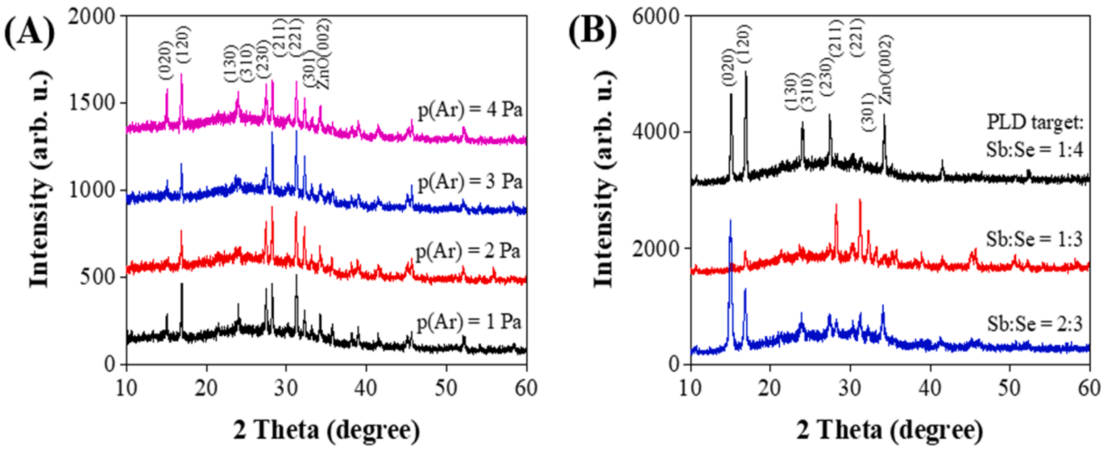


Fig. 6. (A) XRD spectrum of Sb_2Se_3 samples grown by PLD method: (A) under different Ar pressures, and (B) for constant Ar partial pressure (2.5 Pa) samples obtained based on sources with 3 different elements. All Sb_2Se_3 samples were grown on ZnO/glass substrates at a substrate temperature of 300°C

Figure 6A depicts XRD spectra for Sb_2Se_3 thin films grown under different Ar pressures using a source with a Sb:Se ratio of 1:4 at.%. It can be seen that the intensities of the favorable peaks, that is, the intensities of the (hkl, $l \neq 0$) crystal directions, changed under the influence of Ar pressure, where in the films grown under Ar pressure between 2 and 3 Pa (211) and (221) crystal orientations have a higher intensity than the (120) peak. In the following cases, Sb_2Se_3 thin films were grown under a pressure of 2.5 Pa Ar.

Figure 6B shows the XRD spectra of Sb_2Se_3 films obtained at 250°C using sources with three different compositions, i.e. Sb:Se ratio in sources 2:3 at.%, 1:3at. % and equal to 1:4 at.%. Moreover, it was found that the composition of sources has a significant effect on the formation of crystallographic phases. For a source with a stoichiometric ratio (Sb:Se ratio 2:3 at.%) not only (hkl, $l \neq 0$), but also (hkl, $l = 0$) crystal directions were observed, and (hkl, $l = 0$) cho It was observed that the intensity of peaks is relatively high. In particular, the (020) and (120) peaks showed the highest intensity. In the samples obtained on the basis of another source (Sb:Se ratio 1:3 at.%), it grew mainly with (hkl, $\lambda \neq 0$) crystal directions. Among them, the highest intensity corresponded to directions (211) and (221). For the source with the highest Se content (Sb:Se = 1:4 at.%), only (hkl, $l = 0$) peaks were obtained. It seems that not only the substrate temperature but also the Ar gas pressure and the Sb:Se ratio in the source should be taken into account to prepare Sb_2Se_3 in a suitable crystal structure for a solar cell. Taking these into account, the physical properties of the sample obtained in the best condition (samples at a base temperature of 250°C, 2.5 Pa Ar pressure, and a source with a 1: 3 at.% Sb:Se ratio) were studied. Figure 7 depicts the FESEM images of the Sb_2Se_3 thin films discussed in Figure 6B. When the Sb:Se ratio in the source was 2:3 at.%, the (hk0) directions were dominant (Fig. 6B), where 1D $(Sb_4Se_6)_n$ crystal ribbons grew parallel to the substrate surface. In the FESEM image, it can be seen that this tendency has grown crystal grains of different sizes and shapes.

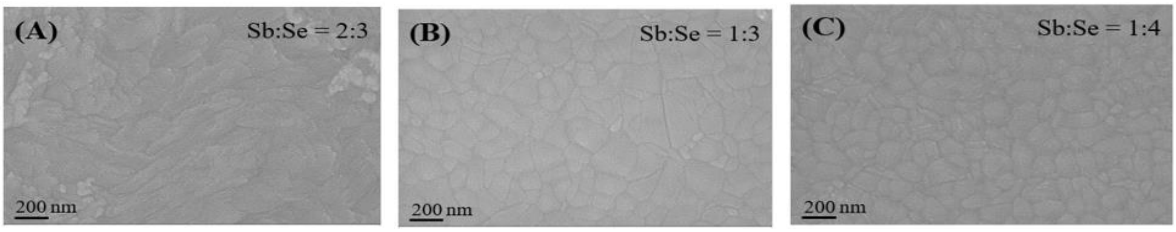


Fig. 7. SEM images of Sb_2Se_3 films prepared based on PLD sources with different Sb:Se ratio (at.%): (A) 2:3; (B) 1:3; and (C) 1:4.

For the Sb:Se = 1:3 at.% case, clear crystal grains are depicted, which is consistent with the XRD results. For the source with the highest Se concentration, i.e. Sb:Se = 1:4 at.%, one can see the mixed state of Sb_2Se_3 crystal grains. In other words, both grain forms observed in Fig. 7A and 7B are present in the sample in Fig. 7C, which confirms that (hk0) and (hk1) crystal directions are formed in this sample (Fig. 6B).

Factors affecting the efficiency of the solar cell include the different distribution of the chemical composition of semiconductor samples in the direction of growth or oxidation of the sample surface over time. In this context, the homogeneity of the chemical composition of the Sb_2Se_3 film along the growth direction and the degree of surface oxidation were investigated.

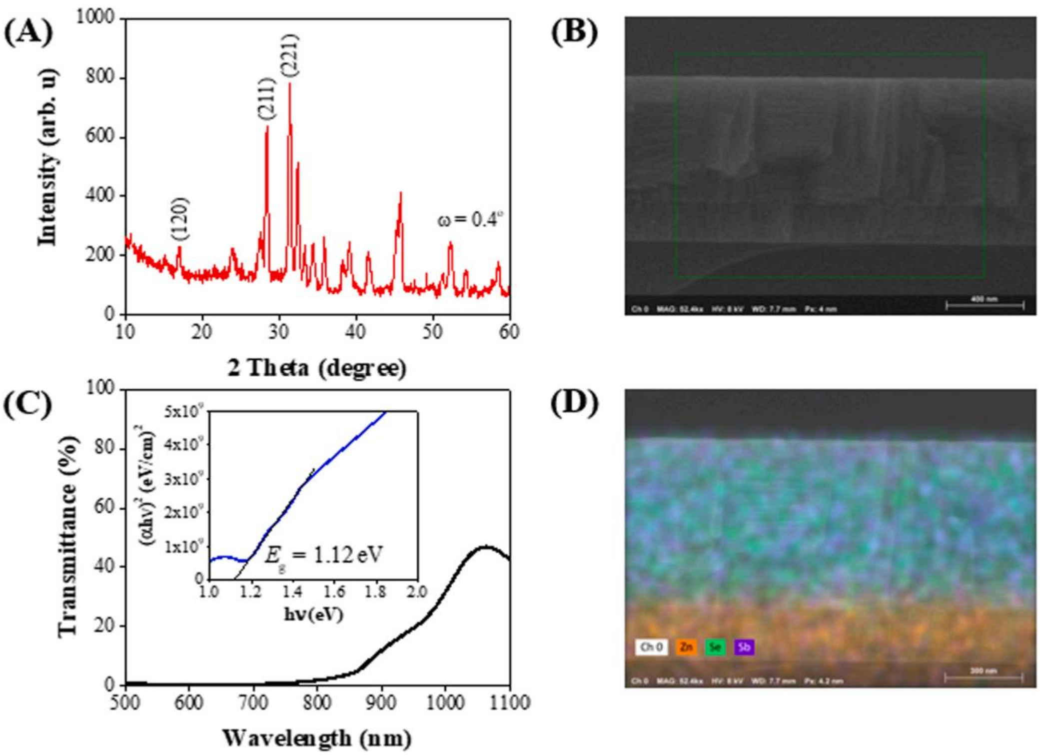


Fig. 8. GIXRD spectrum of (A) 0.4° angle of Sb_2Se_3 samples grown on ZnO/glass substrates by PLD method at 300℃ substrate temperature, (B) SEM image of cross-sectional surface and (D) EDX image of chemical elements. (C) Optical transparency of the Sb_2Se_3 sample (inset: bandgap width of the Sb_2Se_3 sample).

For this, a Sb_2Se_3 sample with the required crystal structure for a solar cell was selected: a source with a Sb:Se ratio of 1:3 at.%; 2.5 Pa Ar pressure; and grown at a base temperature of 250℃. Figure 8A shows the GIXRD (grazing incident XRD) spectrum taken at an angle of 0.4°. As shown, the GIXRD spectrum is almost identical to the XRD result (Figure 6B). That is, the absence of Sb_2O_3 peaks indicates that an oxide layer has not formed on the surface of the sample. 8B and 8D show the cross-sectional view of the Sb_2Se_3/ZnO/SLG structure and the EDX (chemical composition) map, respectively. From this we can see that the Sb_2Se_3 sample was grown without voids and without a chemical composition gradient. Figure 8C shows the optical transparency of the Sb_2Se_3 thin film and the calculated band gap (Eg = 1.12 eV), which corresponds to the theoretically calculated Eg value. This shows that the obtained Sb_2Se_3 thin film in PLD has good optical properties.

Sb_2Se_3 thin films with useful physical properties for an efficient solar cell were successfully prepared using the PLD method. It has been shown that a Se-rich chemical composition can be realized without an additional selenization process. In addition, it was shown that all the parameters of the PLD method must be taken into account simultaneously for the formation of a Sb_2Se_3 thin film with the required crystallographic orientation.

Part II.

2.1. Obtaining flexible, light and two-surface light-harvesting CIGS solar cells

Flexible, lightweight, and bi-surface light-harvesting $Cu(In,Ga)Se_2$ (CIGS) solar cells have several advantages over conventional (made on rigid glass substrates) solar cells, enabling buildings to be roofed and It is suitable for many applications such as surface and automotive coating. In addition, this type of solar cells does not require a layer of glass, which makes up about 80% of the weight of the PV module. In addition, in addition to direct sunlight, the efficiency of solar cells can be significantly increased by simultaneously collecting albedo radiation (light reflected from the earth's surface). allows to increase the level. This can be done through a solar cell with the ability to collect light from two surfaces, because the efficiency of the solar cell increases significantly due to the (simultaneous) collection of light from the front and back surfaces of such a solar cell. This area of my scientific research was carried out in the following order. A bifacial solar cell with the ability to collect light from two surfaces in the "superstrate" structure was prepared on a 50 μm-thick flexible fluorinated ethylene propylene (FEP polymer substrate) polymer base, and its physical properties were studied.

The production of flexible, light and double-surface light-harvesting CIGS solar cells was prepared in three steps as shown in Figure 9. First, standard substrate type solar cells were prepared in the structure Al-Ni / $Zn_{0.9}Mg_{0.1}O$:Al (AZMO) / $Zn_{0.8}Mg_{0.2}O$ (ZMO) / CdS / CIGS / Mo / Ni-Al / SLG (Fig. 9A). CIGS absorber layers with a thickness of 2.5 μm were grown on Mo/SLG substrates using the three-stage evaporation process at a high substrate temperature (~550℃). Then, a 40 nm thick CdS-buffer layer was prepared by chemical bath deposition at 80℃. Then, the second buffer layer (50 nm ZMO) and the transparent electrode (700 nm AZMO) layers were obtained by rf magnetron sputtering method at room temperature. Finally, Al (1.6 μm)/Ni (100 nm) two-layer metal contacts were obtained by electron beam deposition (EB) method. The arrow below shows the manufacturing sequence of the solar cell. Abbreviations used in the figure are as follows: AZMO/ZMO – $Zn_{0.9}Mg_{0.1}O$:Al (2 wt.%)/$Zn_{0.8}Mg_{0.2}O$ transparent electrodes; CIGS – $Cu(In,Ga)Se_2$ absorbing (absorber) layer; SLG - soda glass base; and FEP is a fluorinated ethylene propylene polymer film. The actual images of the solar elements are respectively shown above. After studying the physical properties and performance of this solar cell, in the second step, a 50 µm-thick FEP-polymer film was bonded onto the solar cell at 100℃ using a non-conductive epoxy adhesive and used to separate the solar cell from the Mo/SLG substrate. "the lift-off process" was carried out (Fig. 9B).

Finally, an Al-Ni/ITO/CIGS/CdS/ZMO/AZMO/Ni-Al/Epoxide/FEP structure with a surface area of 0.23 cm^2 was obtained by growing an ITO transparent electrode and an Al/Ni metal layer to form a "superstrate" type structure. solar cells with the ability to collect light from its two surfaces were obtained (Fig. 9C).

The optical properties of the ITO layer were examined using a UV/VIS/NIR spectrophotometer (Shimadzu UV-3600), the electrical resistance and thickness of the samples were measured by the 4-point probe method (NPS, JS TC-400-TF-VR) and was studied on mechanical profilometer (Dektak XT, Bruker) devices. The crystallinity of ITO thin films was investigated by X-ray diffraction (XRD).

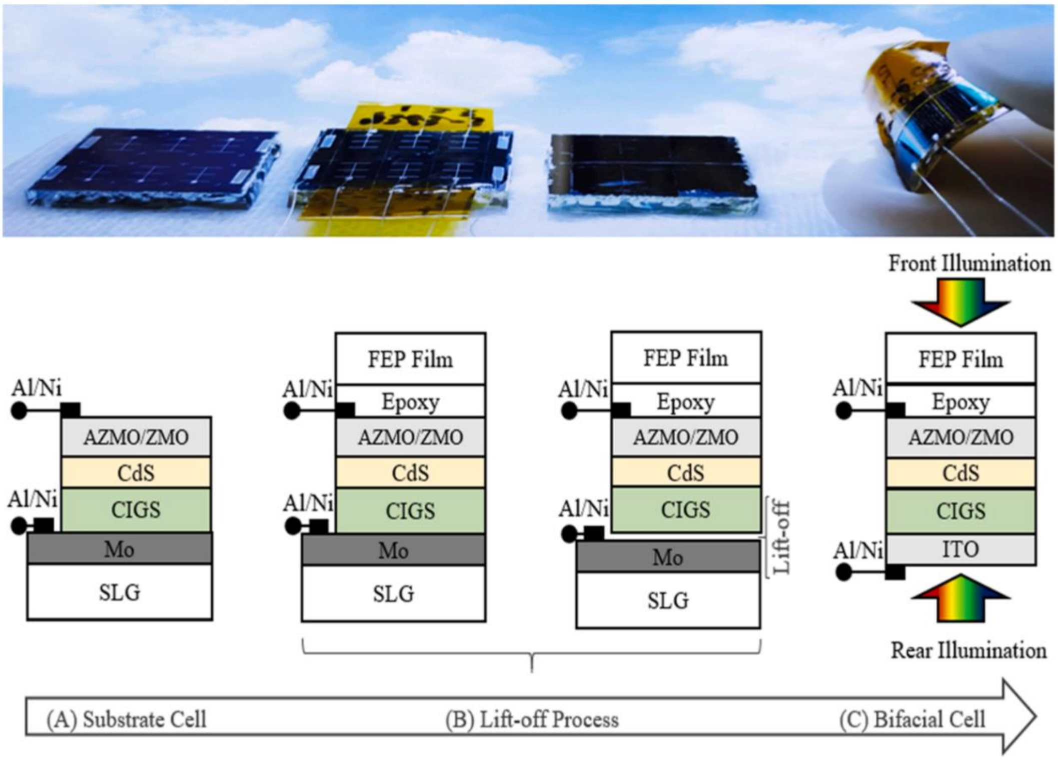


Fig. 9. Schematics of (A) CIGS-based solar cell with standard structure, (B) lift-off method of separating CIGS solar cell from Mo layer, and (C) bifacial solar cell with superstrate architecture.

The mobility and resistivity of ITO thin films were determined using Hall measurements using the Van der Pauw method at room temperature. The J-V characteristics and EQE spectra of double-surface light-harvesting CIGS solar cells were investigated under AM 1.5G (100 mW/cm^2) at 25℃ using CEP-25RR, Bunkoukeiki. Figure 10A shows the J-V characteristics of two standard structured CIGS solar cells fabricated under similar conditions. Despite having the same short circuit density (J_{SC}) values, these solar cells showed different fill factors (FF) and performance.

Solar cells with and without the "S-shape, rollover effect" showed 6.0% and 10.4% efficiency, respectively. To investigate the CIGS/Mo interface, a device with a "rollover effect" was isolated by the "lift-off" method, and a "bifacial" solar cell was formed by growing an TO transparent electrode and Ni/Al metal electrodes. As shown in Fig. 10C, the device efficiency increased to 9.3% for the front surface illumination in the bifacial solar cell.

This result is significantly improved compared to the substrate case of this solar cell (6.0%, red line in Fig. 10A). In addition, 2.3% efficiency was achieved for backlighting. Most importantly, the "rollover effect" observed in the *J-V* characteristic of the substrate-type solar cell (see dashed line in Fig. 10C) disappeared in the bifacial solar cell for both front- and backside-illuminated cases. Since lift-off changes only the back contact of the substrate-type solar cell, and the front-side structure of the FEP/Epoxy/AZMO/ZMO/CdS/CIGS structure remains unchanged (compare Figures 10B and 10D), *J-V* it was assumed that the change of state in the characteristics is related to the CIGS/Mo interface.

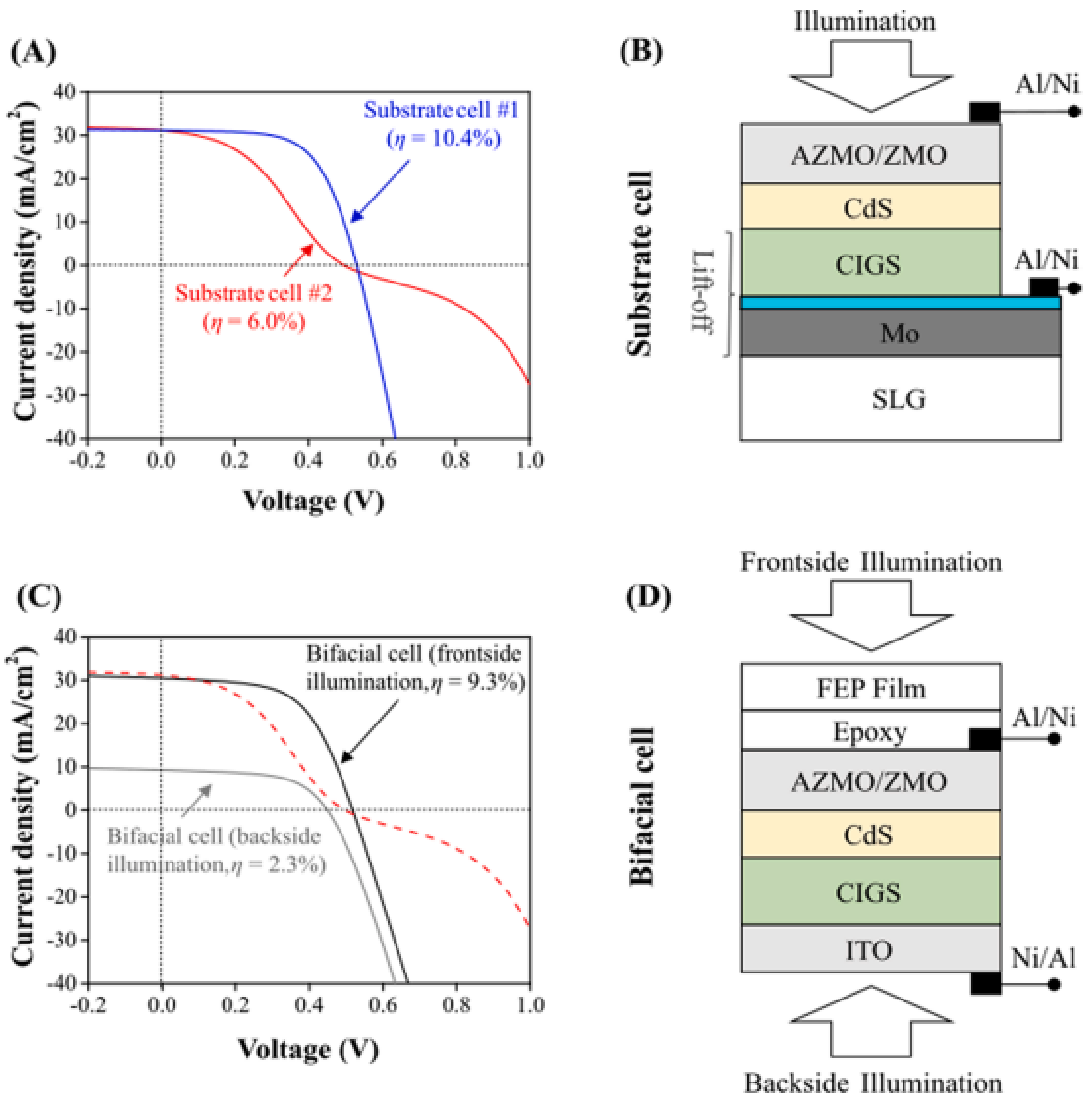


Fig. 10. J-V characteristics of CIGS solar cells in (A) "Standard" and (C) "bifacial" structure. The structures of the devices are respectively (B) Al-Ni / $Zn_{0.9}Mg_{0.1}O$:Al(AZMO) / $Zn_{0.8}Mg_{0.2}O$ (ZMO)/ CdS / CIGS / Mo / SLG and (D) FEP / Epoxide / Al-Ni / AZMO / ZMO / CdS / CIGS / ITO / Ni-Al are indicated. (B) The blue layer in the plot shows the MoSe2 layer.

That is, in the "standard" structure, the potential barrier at the CIGS/Mo interface (for the main charge-carrying "cavities") is reduced after the "lift-off" process. To evaluate this potential barrier height, the temperature-dependent *J-V* characteristics of a substrate-type CIGS solar cell with an efficiency of 7.2% were studied in the temperature range of 200-320 K. Figure 11 shows the J-V characteristic of the CIGS solar cell in the "substrate" structure at temperatures from 200 K to 320 K. As shown, the "rollover effect" is more pronounced at low temperatures, which indicates the presence of a contact barrier for the main charge carriers. In addition, J_{SC} also decreased with decreasing temperature. In the literature, it is stated that the J_{SC} for high-efficiency solar cells is independent of temperature. The increase in J_{SC} with increasing temperature indicated the existence of a potential barrier in the contact area for free charge carriers.

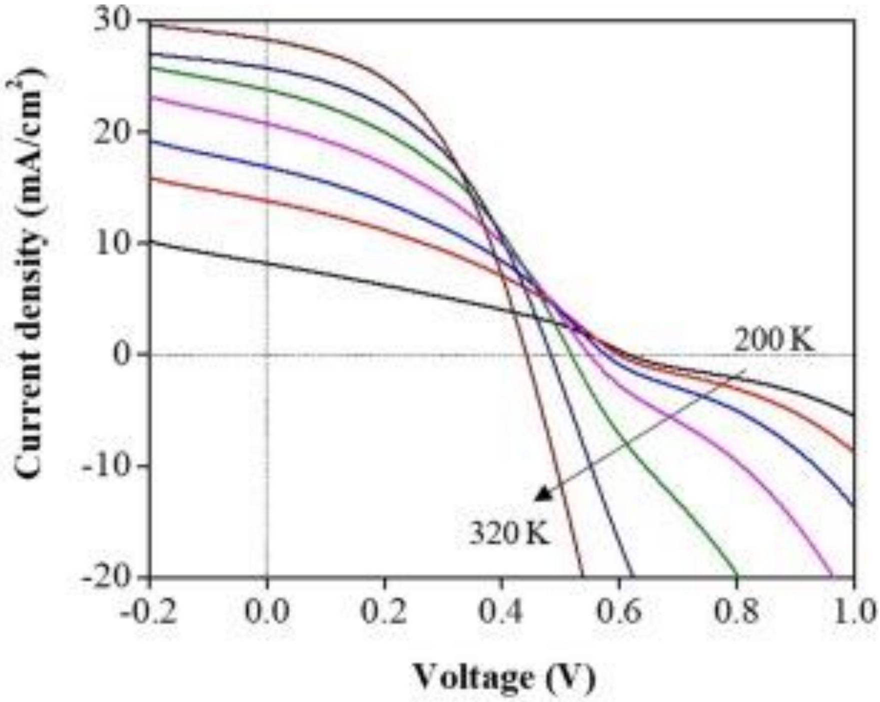


Fig. 11. (A) Temperature dependent J-V characteristics of Al-Ni/ $Zn_{0.9}Mg_{0.1}O$:Al(AZMO) / $Zn_{0.8}Mg_{0.2}O$ (ZMO)/CdS/CIGS/Mo/SLG structural solar CIGS cell in the range of 200-320 K.

Figure 12 shows the GIXRD spectrum measured at an angle of 0.3° for lift-off CIGS and Mo and freshly prepared Mo samples. For CIGS, only CIS and CGS crystal structures are described. The absence of Mo or $MoSe_2$ peaks on the CIGS surface confirms the EDX data, and the "lift-off" indicates that no Mo layer remains on the CIGS surface. However, several crystal structures of the "hexagonal" $MoSe_2$ layer are depicted on the surface of the raised Mo sample, and we can see that they have a higher intensity than the Mo "peaks".

This supports the presence of a $MoSe_2$ layer on the surface of the "lift-off" Mo sample. It is shown in the literature that the $MoSe_2$ layer parallel to the Mo surface does not create a potential barrier. The absence of the (002) peak of $MoSe_2$, i.e., at 13.612° of 2theta, indicates that the $MoSe_2$ grains have grown parallel to the Mo surface, suggesting a “rollover effect” at the CIGS/Mo interface through non-ohmic contact. was found to have formed. For reference, the growth of $MoSe_2$ layer occurs naturally during CIGS layer growth on Mo at high temperature, and the crystal structure of $MoSe_2$ changes depending on CIGS growth parameters.

Thus, there is a need to optimize the $MoSe_2$ layer or improve the ohmic character of the new CIGS/ITO interface for charge carriers. It was shown for the first time in this scientific project that it is possible to control the electrical properties of the CIGS/ITO interface by optimizing the ITO parameters.

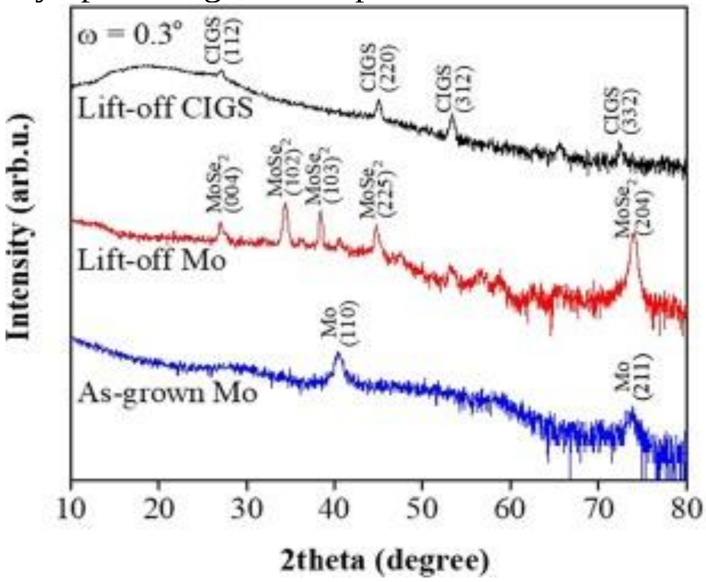


Fig. 12. Grazing-incidence X-ray diffraction (GIXRD) spectrum for lift-off CIGS and Mo layers and freshly prepared Mo layer at an incidence angle of 0.3°. The crystal structures were confirmed by the corresponding JCPDS cards, namely: CIGS ($CuIn_{0.5}Ga_{0.5}Se_2$, JCPDS 40–1488); "hexagonal" $MoSe_2$ (JCPDS 00-015-0029, 01-080-1179) and "cubic" Mo (JCPDS 00-001-1207)

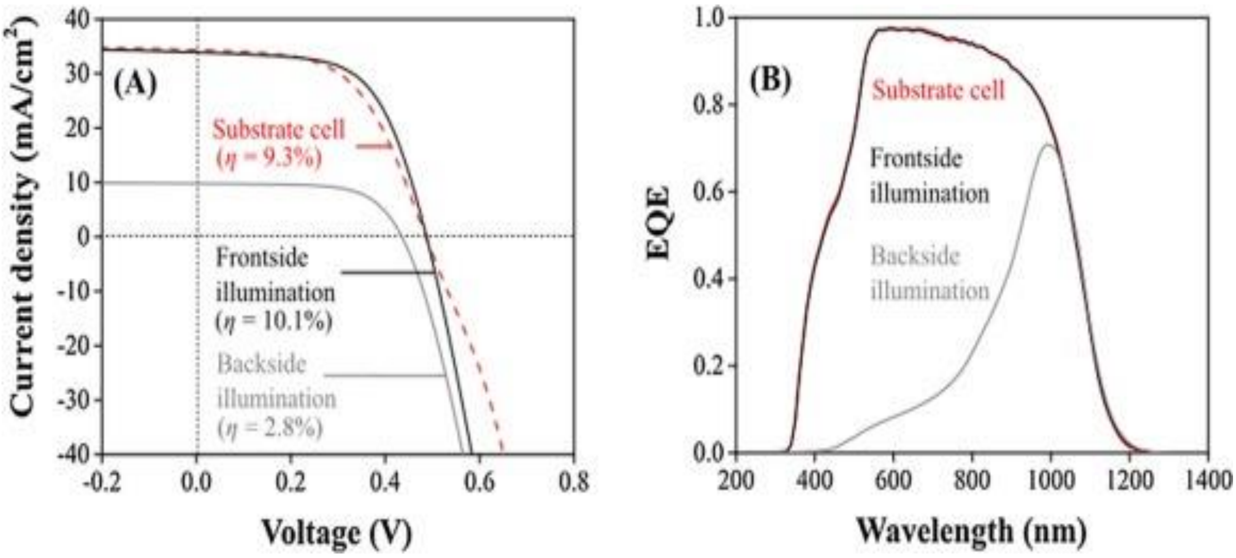


Fig. 13. Al-Ni/ $Zn_{0.9}Mg_{0.1}O$:Al (AZMO)/$Zn_{0.8}Mg_{0.2}O$(ZMO)/CdS/CIGS/Mo/SLG and FEP/Epoxy/Al-Ni/AZMO/ZMO/CdS/CIGS/ ITO/Ni-Al. (A) J-V characteristics and (B) EQE spectra of structured "Standard" and "bifacial" CIGS solar cells.

As an example, Fig. 13 shows J-V characteristics and EQE spectra for CIGS solar cells of "substrate" and "bifacial" type. As can be seen in Figure 13A, the FF of the bifacial solar cell for front illumination is improved due to the reduction of the rollover effect. As a result, the bifacial solar cell showed an efficiency of 10.1% and 2.8% for front and rear illumination cases, respectively. We can see that the "Front" lighting result is higher than "Substrate". This is due to the improved Ohmic contact at the CIGS/ITO interface discussed above. The EQE spectra recorded for these solar cells are similar to literature results. Low EQE spectra were observed in the short wavelength region of the spectrum for rearside illumination. This is due to the fact that the charge carriers generated at the CIGS/ITO interface boundary at short wavelength exposure do not reach the CdS/CIGS domain. In this area, EQE spectra can be improved by reducing the thickness of the CIGS layer and improving the crystalline properties of the CIGS layer.

2.2. Application of solar elements with the ability to collect light from two surfaces to a "tandem" structure.

A bifacial two-terminal perovskite/silicon solar cell was found to perform up to 66% more power than a monofacial solar cell due to the additional R_A = 0.244 light absorption from the rearside surface. The dramatic increase in efficiency in the bifacial two-terminal perovskite/silicon solar cell is mainly due to the reduction of the gap between the J_{SC}s that make up the two solar cells. We can see this from the resulting J-V characteristics of the tandem solar cells in 3 different positions presented in Figure 14.

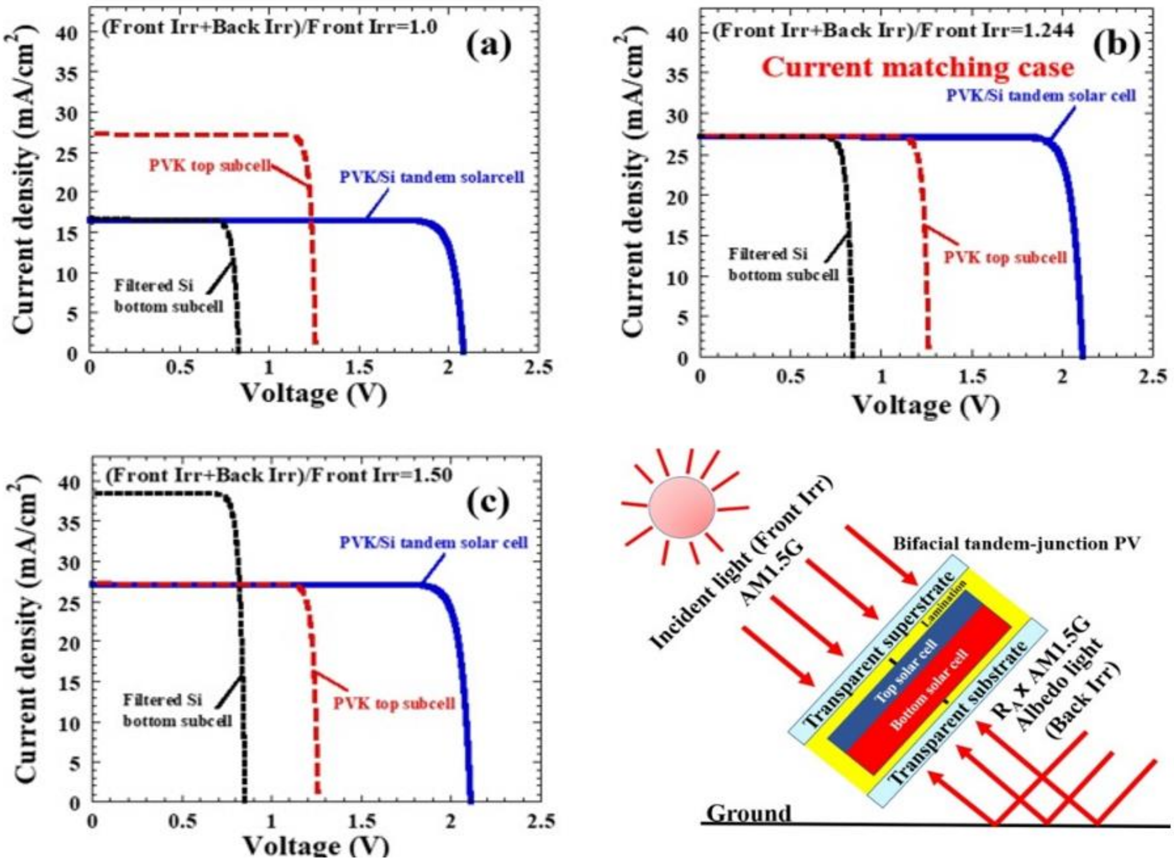


Fig. 14. Schematic view and schematic view of J-V characteristics in 3 different states for a two-terminal "bifacial" tandem solar cell. Front illumination is AM1.5G spectrum and backlight (albedo) is RA × AM1.5G spectrum. RA is the spectral independence, which ranges from 0 (for a single-sided “standard” solar cell with no backlight) to 1.

CONCLUSION

1. Based on the analysis of literature data on Sb_2Se_3 and $Cu(In,Ga)Se_2$, the possibility of creating highly efficient thin-film solar cells based on them, as well as the need to search for new physical-technological methods of their preparation and increasing their efficiency, is shown.

2. The interrelationship between the technological parameters of the deposition process of Sb_2Se_3 thin films, i.e., prepared both in non-vacuum and vacuum environment, and their crystallographic, morphological, optical and electrophysical properties is established.

3. Based on X-ray diffraction results, it has been shown that at low hydrogen flow rates, Sb_2Se_3 samples grew in a Se-rich state, had an amorphous structure, and the intensity of the crystals in the (221) direction was low. In contrast, at high hydrogen flow rates, Sb_2Se_3 layers became Sb showed that it has a rich content, grows with a polycrystalline structure, and its intensity in the (211) direction increases.

4. Based on the experiments, for growing high-quality polycrystalline Sb_2Se_3 thin layers with the (211) and (221) preferred directions in a vacuum environment, the Argon gas pressure is 2 Pa, the source (Sb:Se composition) ratio of 1:3 at.%, and the substrate temperature of ~250°C was found to be optimal growth condition.

5. By optimizing the growth conditions of ITO (In_2O_3:Sn) transparent electrode and Al/Ni metal layer on standard $Cu(In,Ga)Se_2$-based solar cells, "superstrate" type bifacial solar cells with a structure of Al-Ni/ITO/CIGS/CdS/ZMO/AZMO/Ni-Al/Epoxide/FEP and a surface area of 0.23 cm^2 were obtained. As a result, the bifacial solar cell showed an efficiency of 10.1% and 2.8% for front and rear illumination cases, respectively.

6. A bifacial two-terminal perovskite/silicon solar cell was found to yield up to 66% more power than a monofacial solar cell due to the additional R_A = 0.244 (albedo) light absorption from the rearside surface. It has been shown that the sharp increase in efficiency in the "bifacial" two-terminal perovskite/silicon solar cell is mainly due to the reduction of the gap between the J_{SC} formed by the two solar cells.

**НАУЧНЫЙ СОВЕТ DSc.02/27.02.2020.FM/T.110.01
ПО ПРИСУЖДЕНИЮ УЧЕНЫХ СТЕПЕНЕЙ
ПРИ ФИЗИКО-ТЕХНИЧЕСКОМ ИНСТИТУТЕ АН РУз**

ФИЗИКО-ТЕХНИЧЕСКИЙ ИНСТИТУТ

МАВЛОНОВ АБДУРАШИД АБДУВАХОБОВИЧ

ПОЛУЧЕНИЕ ТОНКОПЛЕНОЧНЫХ СОЛНЕЧНЫХ ЭЛЕМЕНТОВ НА ОСНОВЕ $Cu(In,Ga)Se_2$ И Sb_2Se_3 И ИССЛЕДОВАНИЕ ИХ ФИЗИЧЕСКИХ СВОЙСТВ

**01.04.10 – Физика полупроводников
(физико-математические науки)**

**ПРЕДСТАВЛЕНИЕ
ПО ПРИСУЖДЕНИЮ УЧЕНОЙ СТЕПЕНИ ДОКТОРА НАУК (DSc) НА ОСНОВЕ НАУЧНЫХ ПУБЛИКАЦИЙ БЕЗ ДИССЕРТАЦИИ**

Ташкент – 2024

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С презентацией (представлением) можно ознакомиться в Информационно-ресурсном центре Физико-технического института (зарегистрирована за № 381). Адрес: 100084, г. Ташкент, ул. Чингиз Айтматов, дом 2б. Тел./факс: (+99871) 235–42–91.

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(протокол рассылки № _____от «____»_______ 2024 года).

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ВВЕДЕНИЕ (Аннотация представления доктора наук (DSc))

Актуальность и востребованность темы. В мире развитие экологически чистых и возобновляемых источников энергии в качестве альтернативы современным видам топлива (нефть, природный газ, уголь) стало одной из важнейших задач для ученых. Эти усилия направлены на защиту природы Земли путем сокращения загрязнения воздуха, вызванного массовым потреблением нефти, угля и природного газа. На практике замена существующих энергетических технологий новым типом альтернативных источников осуществляется поэтапно. В этом контексте анализ использования энергетических ресурсов называется «Энергетической структурой 21-го века» как «период лучшего МИКСа», включающего различные формы возобновляемой энергии. Фотовольтаические технологии, то есть получение электроэнергии напрямую от солнечного света на основе солнечных элементов, стали одним из самых перспективных среди проектов по разработке экологически чистых технологий производства энергии. Эта технология позволяет генерировать электроэнергию без шума и загрязнения, такого как дым. Выбирая размер фотовольтаического элемента (см. Рисунок 1), эта технология может производить электроэнергию в диапазоне от милливатт (мВт) до мегаватт (МВт).

Обзор зарубежных научных исследований по теме представления.

Научные исследования по изучению физических и технологических свойств солнечных элементов и полупроводниковых материалов, необходимых для их изготовления, проводились ведущими университетами и научными центрами мира, включая университеты Галле, Лейпцига, Магдебурга (Германия), Национальную лабораторию возобновляемых источников энергии, Государственный университет Колорадо (США), Швейцарские федеральные лаборатории по материаловедению и технологии (EMPA), университеты Пармы, Вероны (Италия), Университет Нового Южного Уэльса (Австралия), Университет электронной науки и технологии Китая (Китай), университеты Киото и Рицумейкан (Япония). Научные исследования в этой области проводились постоянно не только в университетах, но и на заводах, производящих такие модули солнечных элементов. Например, можно назвать компании First Solar (США), Oxford PV (Великобритания), CTF Solar, AVANCIS, QCELLs (Германия), Solar Frontier, Panasonic, Sekisui (Япония).

Степень изученности проблемы. Научные исследования по разработке эффективных солнечных элементов проводятся различными исследователями по всему миру. В частности, на основе Si – М. Грин (Австралия); на основе $Cu(In,Ga)Se_2$ – А. Тивари (Швейцария), Р. Шеер (Германия) и Т. Минемото (Япония); и на основе Sb_2Se_3 – Дж. Тан (Китай).

Более 60 лет ведутся работы по солнечным элементам на основе вышеупомянутых и других материалов. Доказано, что возможно практически создавать солнечные элементы с высокой эффективностью. Современные научные проблемы в этой области включают дальнейшее снижение стоимости солнечных элементов, повышение их эффективности и создание различных цветов, световых и гибких подложек.

Под руководством М.С. Тиванова, декана физического факультета Белорусского национального университета, проводятся научные исследования по разработке тонкопленочных солнечных элементов. Под руководством

Т.М. Разыкова, заведующего лабораторией в Физико-техническом институте, ученые из Узбекистана разработали новую технологию, называемую химическим молекулярно-пучковым осаждением, для получения солнечных элементов из двух- и многокомпонентных халькогенидных полупроводников.

Однако до сих пор не изучено получение солнечных элементов на основе бинарного соединения Sb_2Se_3 и $Cu(In,Ga)Se_2$ с использованием метода химического молекулярно-пучкового осаждения. Поэтому изучение условий получения солнечных элементов на основе Sb_2Se_3 и $Cu(In,Ga)Se_2$ и установление законов зависимости электрических и оптических свойств солнечных элементов, полученных рекомендуемым методом в данной презентации, представляет большой интерес как для науки, так и для практики в области полупроводниковых материалов и устройств.

Цель исследования. Получение и физические свойства тонкопленочных солнечных элементов на основе $Cu(In,Ga)Se_2$ и Sb_2Se_3.

Научная новизна исследования заключается в следующем:

впервые исследована связь между физическими свойствами тонких пленок Sb_2Se_3, полученных в вакуумной и невакуумной среде. Установлено, что пленки Sb_2Se_3, осажденные при температуре подложки T ≥ 300°C, с поликристаллической структурой (hkl, λ ≠ 0), растут перпендикулярно поверхности подложки в кристаллическом направлении и стехиометрически богаты Se. Эти пленки имели химическое распределение на поверхности, ширину запрещенной зоны (Eg) 1.12 eV и удельное сопротивление в диапазоне от 10^4 to 10^6 Ohm x cm;

пленки Sb_2Se_3, полученные из источников с атомным соотношением Sb:Se 2:3 и 1:4 в вакуумной среде при температуре T = 250°C и давлении газа аргона 2-3 Па, не только показали (hkl, l ≠ 0), но и (hkl, l = 0) пики относительно высокой интенсивности. Кроме того, в пленках Sb_2Se_3, полученных из источника с атомным соотношением Sb:Se 1:3, показано, что пики (hkl, l ≠ 0) растут перпендикулярно поверхности подложки в направлении кристалла, что установлено методом рентгеноструктурного анализа;

методом энергодисперсионной рентгеновской спектроскопии установлено, что получение тонких пленок Sb_2Se_3 в вакуумной среде при температурах выше 300°C приводит к уменьшению содержания элемента Se в образце;

на основе результатов рентгеновской дифракции, сканирующей электронной микроскопии, метода Холла и методов эллипсометрии определены оптимальные технологические режимы получения тонких пленок Sb_2Se_3 в безвакуумной среде, соответствующие требованиям, предъявляемым к эффективным солнечным элементам;

впервые доказана возможность улучшения производительности методом lift-off для преобразования стандартных тонкопленочных солнечных элементов на основе $Cu(In,Ga)Se_2$ в двусторонние;

впервые показана возможность повышения производительности до 62% с использованием двустороннего солнечного элемента в тандемной структуре за счет значительного снижения потерь энергии.

Научное и практическое значение результатов исследования. Научное значение результатов исследования заключается в возможности формирования эффективных солнечных элементов на основе новых полупроводниковых элементов или соединений. Кроме того, дальнейшее улучшение существующих солнечных элементов, сделав их способными принимать солнечный свет с двух сторон, поможет еще больше повысить их эффективность.

Практическое значение результатов исследования заключается в том, что они будут способствовать дальнейшему развитию экологически чистых, недорогих и высокоэффективных тонкопленочных солнечных элементов в больших масштабах.

Внедрение результатов исследования. Научные результаты по разработке образцов и тонкопленочных солнечных элементов на основе $Cu(In,Ga)Se_2$ и Sb_2Se_3 были использованы в работах зарубежных исследователей, в частности для объяснения физических свойств солнечных элементов на основе этих образцов и повышения их эффективности. Список цитирований этих научных работ в базах данных «Web of Science» и «Scopus» превышает 1000 (по состоянию на октябрь 2023 года), некоторые из которых приведены ниже:

Результаты, полученные на основе исследования морфологических, структурных, оптических и электрических свойств тонких слоев Sb_2Se_3 различного состава, послужили оптимизации параметров слоев Sb_2Se_3. Эти результаты были использованы в следующих исследованиях в зарубежных журналах, посвященных изучению электрических и оптических свойств слоев селенида сурьмы и солнечных элементов на их основе (Solar Energy Materials and Solar Cells. Impact Factor: 7,267. Vol. 200, 15 September 2019, 109945; Solar Energy, Impact Factor: 5,95. Vol. 187, 15 July 2019, Pages 404-410; Solar Energy, Impact Factor: 5,95. Vol. 188, August 2019, Pages 586-592). Полученные научные результаты позволили улучшить морфологию и структуру слоя Sb_2Se_3 в результате его применения в научно-технических и технологических процессах подготовки слоев. В результате был создан тонкопленочный солнечный элемент на основе Sb_2Se_3 с КПД 5,6%.

Наличие контактного сопротивления и электрического потенциала, наблюдаемого на поверхности $Cu(In,Ga)Se_2$/ITO, позволило объяснить эти научные проблемы в солнечных элементах на основе других типов полупроводниковых материалов. В частности, это использовалось для разработки поверхностей Sb_2Se_3/Fe_2O_4(FeS) (Solar Energy, Impact Factor: 6,7. Vol. 249, 1 January 2023, Pages 414-423). Кроме того, это применялось в разработке солнечных элементов на основе $Cu(In,Ga)Se_2$/ITO с полупрозрачными оптическими свойствами и улучшенной стабильностью (Solar RRL, Impact Factor: 8,31. Vol. 6, 17 February 2022, 2101071). Более того, это применялось для повышения эффективности солнечных элементов на основе p-типа CZTSSe (Journal of Materials Science: Materials in Electronics, Impact Factor: 2,48. Vol. 32, 7 August 2021, Pages 22535-22547). Этот концепт также был принят для широкозонных халькопиритовых солнечных элементов для демонстрации применимости материала ITO (Solar RRL, Impact Factor: 8,31. Vol. 6, 18 May 2022, 2200401). Наиболее важно, что было установлено, что эффективный солнечный элемент также может быть получен с использованием химически подготовленного $Cu(In,Ga)(S,Se)_2$ на поверхности ITO (Advanced Materials Interfaces, Impact Factor: 6,39. Vol. 10, 1 September 2023, 2300566).

Наши научные исследования по формированию слоя $MoSe_2$ на интерфейсе $Cu(In,Ga)Se_2$/Mo использовались для увеличения Voc солнечного элемента на 100 мВ, уменьшения ёмкостного сопротивления, образующегося на задней поверхности, и подготовки эффективных солнечных элементов при низких температурах (Nature Energy, Impact Factor: 27,05. Vol. 8, 21 November 2022, Pages 40-51; Advanced Functional Materials, Impact Factor: 19,41. Vol. 33, 20 July 2023, 2303188; Progress in Photovoltaics: Research and Applications, Impact Factor: 8,05. Vol. 30, 21 October 2021, Pages 191-202). Этот концепт также использовался в солнечных элементах Sb_2S_3 с использованием подложки из Mo (Advanced Science, Impact Factor: 17,52. Vol. 10, 5 September 2023, 2303414).

Публикация результатов исследования. Результаты исследования на степень доктора наук (DSc) отражены в более чем 35 научных статьях, опубликованных в престижных научных журналах как Q1/Q2, рекомендованных Высшей аттестационной комиссией при Министерстве высшего образования, науки и инноваций Республики Узбекистан.

ЗАКЛЮЧЕНИЕ

1. На основе анализа литературных данных по Sb_2Se_3 и Cu(In,Ga)Se_2 показана возможность создания высокоэффективных тонкопленочных солнечных элементов на их основе, а также необходимость поиска новых физико-технологических методов их изготовления и повышения эффективности.

2. Установлена взаимосвязь между технологическими параметрами процесса осаждения тонких пленок Sb_2Se_3, то есть подготовленных как в безвакуумной, так и в вакуумной средах, и их кристаллографическими, морфологическими, оптическими и электрофизическими свойствами.

3. На основе результатов рентгеновской дифракции показано, что при низких расходах водорода образцы Sb_2Se_3 росли в состоянии, насыщенном Se, имели аморфную структуру, и интенсивность кристаллов в направлении (221) была низкой. Напротив, при высоких расходах водорода слои Sb_2Se_3 становились насыщенными Sb, росли с поликристаллической структурой, и их интенсивность в направлении (211) увеличивалась.

4. На основе экспериментов для выращивания высококачественных поликристаллических тонких слоев Sb_2Se_3 с предпочтительными направлениями (221) и (211) в вакуумной среде было установлено, что оптимальными условиями роста являются давление Аргона 2 Па, соотношение исходных материалов (Sb:Se) 1:3 ат.% и температура подложки около 250°C.

5. Оптимизировав условия роста прозрачного электрода ITO (In_2O_3:Sn) и металлического слоя Al/Ni на стандартных солнечных элементах на основе Cu(In,Ga)Se_2, были получены двусторонние солнечные элементы типа «суперстрат» со структурой Al-Ni/ITO/CIGS/CdS/ZMO/AZMO/Ni-Al/эпоксид/FEP и площадью поверхности 0,23 см². В результате двусторонний солнечный элемент показал эффективность 10,1% и 2,8% при освещении спереди и сзади соответственно.

6. Было установлено, что двусторонний двухконтактный перовскитный/-кремниевый солнечный элемент генерирует на 66% больше энергии, чем однонаправленный солнечный элемент, за счет дополнительного поглощения света R_A = 0,244 (альбедо) с задней поверхности. Показано, что резкое увеличение эффективности в «двустороннем» двухконтактном перовскитном/кремниевом солнечном элементе главным образом обусловлено уменьшением разрыва между $J_{кз}$, формируемым двумя солнечными элементами.

E’LON QILINGAN ISHLAR RO‘YXATI
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