RESEARCH ARTICLE OPEN ACCESS

BeIon Implantation For In As Diodes Fabrication

Sriram Pradhan, Subham Sourav Dhar
Gandhi Institute of Excellent Technocrats, Bhubaneswar, India
Nigam Institute of Engineering and Technology, Bhubaneswar, Odisha, India

ABSTRACT— Be ion implantation and annealing conditions wereoptimized to demonstrate an effective method for selective areap-type doping in InAs. Optimized implantation and annealingconditionsweresubsequentlyutilized to produce planarInAsdiodes. The Beimplanted planardiodes hadasuperiordynamic resistance-area product and comparable dark currentwithn-i-pInAsmesadiodeswhenoperatedatlowtemperatures.
Index Terms— Annealing, indium arsenide, ion implantation, photodiode.

I. INTRODUCTION

InAsisconsideredakeyIII–Vsemiconductorinthefieldsofhighspeedandoptoelectronics duetoitshighelectronmobilityandlargebandoffsetattheInAs/AlSbheterojunction.Inaddition,InAshasbeenshowntoexhibitverylowexcessavalanchenoise[1]and hasapeakpho-toresponsecloseto3.4μm,whichisideallysuitedformethanegassensing.ThemajorityofreportedInAsdevicesaremesastructuresgrownbymolecularbeamepitaxy(MBE)ormetal-organicvaporphaseepitaxy(MOVPE).Despitetheknownadvantagesofplanarstructures,planarInAsdevicesareseldomreported.Thisfactstemsfromanunderdevelop-mentinselectiveareadoping techniques, suchasdiffusionorionimplantation,whicharecrucialforplanardevicefabrication.InthedrivetodevelopplanarInAsdevices,IwamuraandWatanabe[2]reportedonZndiffusiontech-niqueswhichhavebeenutilizedtoproduceplanarInAs diodes.However,complicationsassociatedwiththediffusiontechniquesmakeitdesirabletoexplore otherdoping methods;forexample,whendiffusingZnintoInAs,the hightem-peratureenvironmentnecessitatesanAsoverpressuretobemaintained inthechamber toprevent thedissociation ofAsfrom the InAs. Consequently, Zn diffusion into InAs has oftenbeencarriedoutinaMOVPEreactor,whichsignificantlyincreasesthecostandcomplexityoftheprocess[2],[3].Furthermore,aprotectivemaskthatmatchesthethermalexpansioncoefficientofInAsisnotreadilyavailable,andsothermallymismatchedmasksarecommonlyused.Comparedwithdiffusiontechniques,ionimplantationhastheadvantage ofbeingalowtemperatureprocesstherebyavoidingthe complications associated with the high temperature processingofInAsstatedabove;inaddition,alargevarietyofdopantsandmore intricate doping profiles are achievable. Ion implantationofthelightgroupIIaelements,BeandMg, hasprovedpopularforp-typedopinginavarietyofIII–Vsemiconductorssuchas InSb [4] and GaAs [5]. The popularity of these particularelements is owing to the low implant damage inflicted duringthe implant and the excellent damage removal through postim-plant annealing, which can be a major drawback of dopingIII–V semiconductors using ion implantation [6]. Mg implan-tationintoInAswasfoundtobeineffectiveforp-typedoping, and it isspeculated that the radiation defects can-celledouttheusualacceptorlikebehaviorofMgresult-inginaneutralnetdoping[7].However,Wang et al. [8]reported on the damage accumulation and lattice strain of Beimplanted InAs. Using an implant energy of 80 keVand adoseupto4 10^{13}cm^{-2},cre×atingapeakBeconcentrationof 1.1× 10^{18}cm^{-3},minimallatticestrainisintroducedtothe crystalandonlypointdefectsareformedaftertheimplant.TheBeprofilebefore andafterannealing ofBeimplantedInAs has been reported by Gerasimenkoetal. [9], [10]. WhencomparingtheBeprofileagainstasimulationgeneratedusingsoftwarepackageTransportofIonsinMatter(TRIM)[11],errors in the straggle of up to 24% were found. In addition, thesevere diffusion of Bewhen annealed attemperatures greaterthan450°Contimescalesof30minuteswashighlighted.Be implantation has not been utilized to produce InAs devices,northeelectricalpropertiesofBeimplantedInAsbeentested.Thekeycontributionsofthispaperare:1) Beimplantationandannealinghavebeendemonstrated asaneffectivemethodforselectiveareap-typedopingInAs;2)implantandannealingconditionshavebeenoptimizedtomaximizetheelectricalperformanceofInAsdiodes;3)secondary ionmassspectrom-etry(SIMS)measurementswereusedtoobservethediffusionofBecausedbyannealing;and4)high-qualityBeimplantedplanarInAsdiodeshavebeendemonstrated withcomparable darkcurrentstoeptiaxiallygrownn-i-pmesaInAsdiodes.

II. EXPERIMENTAL DETAILS

Two InAs i-n structures were used in this paper. The firststructure, hereafter, referred toaswaferA,was grown byMBE at approximately 490 °C and consisted of a 3.5 μmintrinsiclayerona2μmSi-dopednlayergrownonan$^+$InAs substrate. Thesecond structure, waferB,wasgrownusing MOVPE with a susceptor temperature of 590 °C andconsistedofa6μmthickintrinsiclayerona2μmSi-dopednlayer grown on a n$^+$InAs substrate. Beion implantationwas used to define ap-type doping profile in each of thestructures.WaferAwassubjecttoauniformblanketimplant

ofBeandsubsequentlyusedtofabricateallofthemesadiodespresentedinthispaper.WaferBwaspatternedwith adielectricmaskbeforeimplantationandsubsequently usedto fabricate all of the planar diodes presented in this paper.TRIM was used to model the distribution of Be ions implantedinto InAs. Simulations predicted that a flat doping profile to adepth of 0.75 μm, with the junction extending a total of 1 μm,could be realized from two $_9$Beimplants with conditions of200 keV at 110^{14} cm^{-2} and 70 keV at 3.810^{13} cm^{-2}. Theimplantation was carried out at University of Surrey Ion BeamCenter.A1μmpregionwaschosentolimitthedamagetothe crystal. The beam current was set to 20 μA to avoid anylocalized heating of the wafers. The wafers were held 7° offthebeamaxistowardthe(100)crystalplaneduringtheimplantto avoid channeling effects and to enable comparisons againsttheTRIMmodel.

Ithasbeenreportedthattheimplanttemperaturecanhave apronounced effect ontheresultingcrystal qualitywithincertain III–V semiconductors, such as InP [12], however, nosuch information exists for InAs. To investigate the effects ofsuch dynamic annealing in InAs, implants were carried out onsamples held at room temperature (RT), 100 °C and 200 °C.After implantation, the samples were annealed at temperaturesranging from 450 °C to 700 °C for 30 s in a nitrogen richatmosphere. Gerasimenkoet al. [10] showed that significantBe diffusion occurs at temperatures as low as 400 °C, andthereforetominimizetheBediffusion,rapidthermalannealing(RTA) was utilized. Precautions were taken to preserve thestoichiometryatthesurfaceofthesemiconductorduringannealing.Afterannealing,andinthecaseofwafer A,circularmesa diodes of varying diameters were fabricated using a typi-cal photolithographic and wet chemical etching technique [13].Ti/Au was deposited as top and back contacts. The removal ofradiationdamage,whichisinherentlyconnectedtotheimplantprocess,wasanalyzedthroughcomparisonsofthedarkcurrentof the mesa diodes. Appropriate annealing conditions wereevaluated along with a discussion of the influence of sub-strate temperature during implantation. Optimized implant andannealing conditions were subsequently employed to produceplanar diodes from wafer B. After annealing, the planar diodeshad metal contacts deposited. Current–voltage measurementswere performed using anAgilent B5100 parameter analyzerbyprobingthediodes.

III. RESULTS AND DISCUSSION

Thecurrentdensity–voltage (J–V)characteristicsofdiodesfrom wafer A, implanted at RT and annealed at temperaturesfrom 450 °C to 700 °C for 30 s are shown in Fig. 1. Anunan-nealeddiodefromwaferAisalsoshown.Incomparingthe J –Vcharacteristic ofan unannealed diode against oneannealed at 450 °C, no improvement is observed. It is difficultto identify whether the slight rectifying behavior observed inboth diodes was due to Be activation, or if a Schottky junctionat the metal semiconductor interface was the cause. However,inanycase,the similaritybetweenJ –Vcharacteristicsofunannealed diodesandthoseannealedat450°Csuggeststhatsignificant Beactivationandcrystal recoveryhasnot

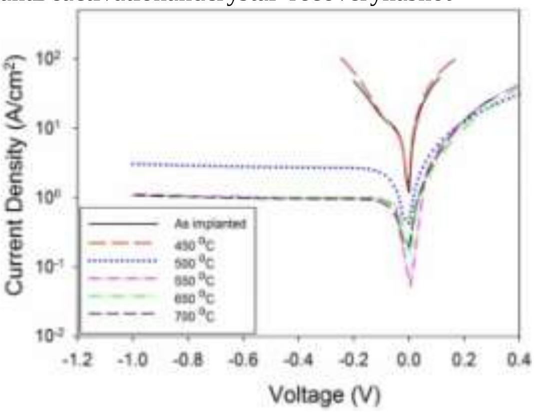

Fig.1.J –VcharacteristicsofmesaInAsdiodesimplantedatRTandannealed at 450 °C, 500 °C, 550 °C, 650 °C, and 700 °C for 30 s. In addition,theJ–VcharacteristicsanunannealeddiodeimplantedatRTisshown.

occurred. Diodes annealed at 500 °C displayed a pronouncedrectifying behavior, however, the lowest dark current densitywasmeasuredindiodesthathadbeenannealedattemperaturesof 550 °C–700 °C. Diodes annealed in this temperature rangeproduced very similar J –V

characteristics with a dark currentdensity of 1 $Acm^{-2}$and a forwardJ –Vcharacteristic thatwaslimitedbytheseriesresistanceofthesemiconductor-metalinterface.Itisapparentthatthemaximumrecoveryis achieved from annealing at a temperature of 550 °C, andhigher annealing temperatures do not encourage further levelsof recovery to reduce the dark current density of the resultingdiodes. However, this does not necessarily indicate that theannealing has fully eradicated all of the implant damage; ofteninIII–Vsemiconductors thereisresidualimplantdamage,whichisimmunetodissociationthroughannealing.
Hotimplantshavebeenshowntomitigatetheimplantdamage leading tohigher quality crystalafterannealing. TheJ –Vcharacteristicsofdiodesimplantedat RT,100 °C, and 200 °CareshowninFig.2.Inadditiontothis,samplesimplantedatRT,100 °C, and 200 °Candannealed at 500 °C and 550 °C are also shown. The annealingtemperatureclearlysegregatestheJ –Vcharacteristicsofthediodesintothreedistinctbands. Withineachband,theJ –Vcharacteristics of diodes from the hot implants closelyresemblethosefromtheRTimplantstudy.Therefore, theimplant temperature is seen to have a negligible effect on theresulting device J –Vcharacteristics. This result is similar tothat obtained in various other studies, such as Be implantationintoInP[14].
Our dark current characteristics confirm that Be has beensuccessfullyimplantedandactivated.Wenowfocusourattention tothe Beprofile withinour samples. Fig. 3showsBe profiles before and after postimplant annealing as mea-suredbySIMS.TheBeprofilegeneratedusingTRIMisincluded for comparison. Discrepancies seen in the absolutevalue of the Be concentration in the TRIM and SIMS resultsare likely to be caused by a calibration error of the SIMSmeasurement.UnannealedsamplesatRTand200°Cshowed

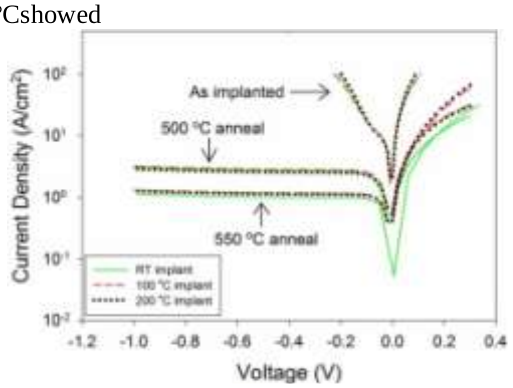

Fig. 2.J –V characteristics of mesa InAs diodes which were implanted at RT,100°C, and200°C.In addition,theJ –Vcharacteristicsofdiodesannealedat 500 °C and 550 °C for 30 s from the three implant temperatures are alsoshown.

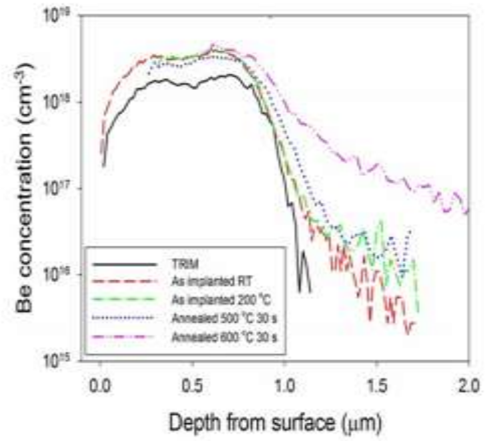

Fig.3.TheconcentrationofBeafterimplantationintoInAsat:roomtemperature; 200 °C; room temperature and annealed at 500 °C for 30 s; androom temperatureand annealedat 600 °C for 30 s. In addition, a simulatedBeprofilegeneratedusingTRIMisshown.

Identical Be distributions down approximately 310^{16} cm^{-3},showingthatthesubstratetemperature doesnot affecttheresulting Be profile. The 70 and 200 keV implants producedBeconcentration peaks at0.29 and 0.64 μm,respectively.Whenthetailofthe200 keVimplantiscompared againstthe TRIM model, the SIMS results showed that the projectedrange was slightly shorter and the straggle was greater thensimulated. Results are summarized in Table I. Previous workreported errors of up to 24% in the straggle but the projectedrangewasfoundtobeaccurate[9]. OurcomparisonshowedTRIMtobeinmuchbetteragreementwithexperimentaldata.However,thediscrep-ancybetweenstudiesmaybeduetoincreasedioninter-actionswithdefectsin higherdoses. SamplesimplantedatRTandannealedat500°C and600°C for30swereincludedintheSIMSanalysis.Aslightredistri-butionofBewas observedwhen annealingat 500 °CasthepeakconcentrationofBe had reducedby16%andtheBetailextendingintothesample hadbroadened.

TABLEI
SUMMARIZED RESULTSANALYZING THE TAIL OF BeDISTRIBUTION FROM TRIMAND SIMSMEASUREMENTS

Sample	Projected Range (nm)	Straggle (nm)	Peak Concentration (cm^{-3})
TRIM	700	130	2.0×10^{18}
SIMS *(Unannealed, implanted at RT and 200 °C)*	645	147	4.0×10^{18}
SIMS *(Implanted at RT, annealed at 500 °C for 30 s)*	-	175	3.4×10^{18}

The Beprofile of thetailafter theanneal hasbeen mod-eledbyaGaussiandistributionwiththeresultssummarizedin Table I. The redistribution of Be resulting from a 600 °Canneal for 30 s was much more severe, resulting in a distortedBe profile that could not be modeled by a Gaussian distri-bution.ThepeakBeconcentration inthesampleannealedat600°Cfor30swasfoundtobeslightlylargerthanthe unannealed samples, suggesting another mechanism otherthan diffusion may be occurring. A similar observation wasreportedforMgimplantsintoInAs[7];theexplanationofferedwas that, during annealing, the highly mobile Mg tends togatheraroundradiationdefectsformingMgclusters.Itispossible that Be behaves in a similar manner to Mg duringhightemperatureannealing.Annealingat550°C appearstobethe optimum annealing condition to achieve low dark currentsandmaintaintheimplantedBeprofile. Havinganalyzedtheeffectsofimplanttemperatureand postimplant annealing, we used our results to fabricate planardiodes on a sample from wafer B. Planar diodes of varyingdiameterswerefabricatedusingRTionimplantationandannealing conditions of 550 °C for 30 s. TheJ –Vcharac-teristics of the resulting diodes are shown in Fig. 4. Strongsimilarities exist between the J –V characteristics of the planardiodes, and themesa diodes shown in Fig.1, allhaving adark current density of 1 Acm^{-2}, which remains relatively flatthroughthevoltagerangemeasured.Theplanardiodesshowedbulkdominated darkcurrent andgood confinement ofthedepletion region as shown in Fig. 4 by scaling the dark currentof various sized diodes with their respective active areas. Suchstrong correlation between the dark current density of varioussized diodes could only be attained if the p-n junction wasformed at the boundary of the p-type implanted region. Thesefeatures are desirable for the development of closely spacedInAsphotodiodearrays.
TheRTand200KJ–VcharacteristicsofaZndiffused planardiodefromIwamuraandWatanabe[2],aMOVPEgrownmesadiodefromKer et al.[15]andacommercialphotodiode from Judson are also plotted in Fig. 4. At0.1 V,thedarkcurrentdensityoftheBeimplanteddiodeswerefound tobe largerthan thatofthereference diodes whenmeasured at RT. However, at 200 K, the dark current densityoftheBeimplanteddiodehasreducedbyoverthreeorders

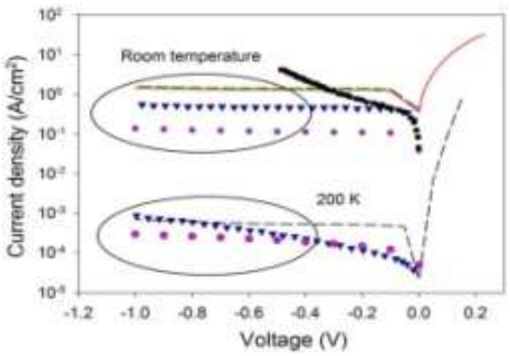

Fig. 4.J –V characteristics of 100, 200, and 300 μm diameter Be implantedplanarInAs diodesatRTareshownbyadashedanddottedgreenline, solid red line, and dashed black line, respectively. The J –V characteristic of a 300-μmdiameterBeimplantedplanarInAsdiodeisalsoshownat200Kbya dashed black line. The J –V characteristics of a Zn diffused planar diode [2] (inverted blue triangles), an MOVPE grown mesa diode [15] (pink

circles),andacommercialphotodiodefromJudson(bla cksquares)areshownatRTand200K.

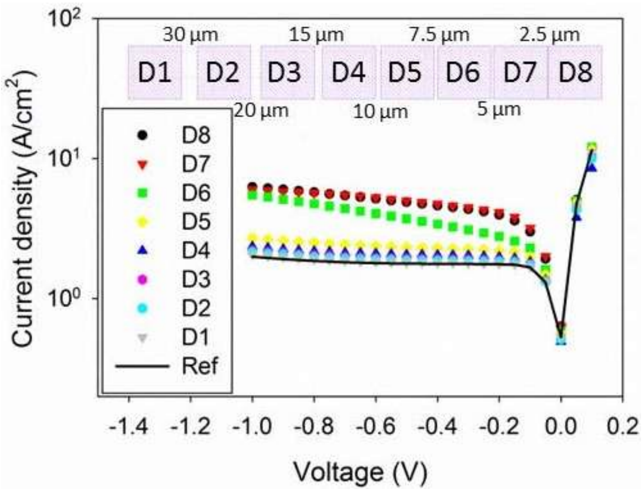

Fig. 5. Schematicdiagramof the lineararray of 100 µm square planarInAsdiodesfabricatedwiththevariousseparationdistances(insert).TheJ –Vcharacteristics of the diodesfrom the lineararrayare shown in additiontotheJ–Vcharacteristicsofanisolatedreferenceplanardiode.

of magnitude. The dark current density of the Zn diffuseddiodeandthemesadiodehadalsoreducedbyas imilaramount at this temperature. However, the dark current densitywas found to increase significantly with reverse bias, whereasthe dark current density of the Be implanted diode remainedrelatively constantacrossthevoltagerange. Owingtothisfact, the maximum dynamic resistance-area product (R_dA) oftheBeimplanted diodes wasmeasured tobe 12.1 k▲cm^{-2}at 0.3Vwhichislargerthanthatofa Zndiffusedplanardiod e [2]orn-i-pmesadiode[15]withR_dAsof2.9and6k▲cm^{-2}at0.1an d0.75V,respectively.

Be implantation and annealing techniques discussedinthispapercouldbeusedtofabricate an array ofInAsphotodiodesforimagingapplications.Itis,there fore, usefultoconsidertheperformanceofthediodeswhenin anarraygeometry.Asapreliminarystudy,alineararray of100-µm square diodes wasfabricated withvarious separationdistances between neighboring diodes. The J –Vcharacteristicofeachdiodeinthelineararrayisshown inFig.5alongwiththeJ–Vcharacteristicfromareferenceof100-µmdiameterplanardiode.Thereferencediodewasloca tedover120-µmawayfromanyotherdiodeandcanbeconsideredasd ecoupledfromanyotherdevice.Aschematicofthelinea rarrayisshownintheinsetofFig.5.DiodesD6,D7,andD 8havehigherdarkcurrentsthanthereferencediodeindi catingincompleteisolationwhenthegapbetweendiode sis<5µm.Fordiodeseparationabove7.5µm,thedarkcu rrentsfromD5toD1werefoundtoasymptoticallyappro achthedarkcurrentofthereferencediode.Thezerobias darkcurrentofdiodesD5–D1iswithin ±6%ofthereferencediode.Furtheroptimizatio nofimplantationandannealingconditions,useofadditi onalimplantationtoincreasetheresistivityofInAsorus eofisola-tiontrencheswillberequiredtoreducetheseparationdis tance.Theopticalproperties oftheplanardiodesarenowinves-tigated.Theresponsivityofaplanardiodewasmeasure dat1550nmusingaHeNelaserwiththeopticalspotfocu sedonthep-typeregionofthediode.Thephotocurrentwasmeasure datroomtemperatureusingphasesensitivedetectionan dfoundtobe0.45A/Wwithoutanyantireflection(AR)c oating. Further work to increase the minority carrier diffusionlengthand the useofan ARcoatingcouldimprovethisfigure.

IV. CONCLUSION

Beimplantationhasbeendemonstratedasane ffectivemethod for selective area p-type doping InAs. The implantprocess appears to be destructive, typically resulting in poorelectricalcharacteristicsofunannealedmaterial,h owever,good recovery can be achieved using RTA. Annealing at atemperature of 550 °C provided the optimum conditions interms of producing the lowest dark current in mesa diodes andpreserving the as-implanted Be profile. Higher annealing tem-peraturesdidnotproducebettercrystalqualityandonly causedfurtherBediffusion.ImplantscarriedoutatRTw erefoundtobe justas effective ashot implants. Planar InAs diodeswere demonstrated by utilizing the optimized Be implantationtechniques discussedin thispaper. The dark current densityof the Be implanted planar diodes was found to be larger thanthat of an InAs Zn diffused planar diode and mesa diode whenmeasured at RT. However, at 200 K, the J –Vcharacteristicsweremuchmorecomparable, andthemaximumR_dAoftheBeimplanteddiodewasfoundtobelargerthanthatoftheZn diffused planar diode and mesa diode. The lateral junctionconfinement of the planar diodes was investigated in an arraygeometry andadiodeseparation of7.5µmwasfound toelectrically isolate neighboring diodes. The responsivity of theplanardiodeswasfoundtobe0.45A/Wat1550nm.

REFERENCES

[1] A. R. J. Marshall, C. H. Tan, M. J. Steer, and J. P. R. David, “ExtremelylowexcessnoiseinInAselectronavalanchephotodiodes,”IEEEPhoton.Technol.Lett.,vol.21,no.13,pp.866–868,Jul.1,2009.

[2] Y.IwamuraandN.Watanabe,“InAsplanardiodefabricatedbyZndiffusion,”Jpn.J.Appl.Phys.,vol.39,no.1,pp.5740–5745,2000.

[3] A.Säynätjokietal.,“InAspixelmatrixdetectorsfabricatedbydiffusion of Zn in a metal-organic vapour-phase epitaxy reactor,” Nucl.Instrum.MethodsPhys.Res.,vol.563,no.1,pp.24–26,Jul.2006.

[4] C. E. Hurwitz and J. P. Donnelly, “Planar InSb photodiodes fabricatedby Be and Mg ion implantation,”Solid-StateElectron., vol. 18, no. 9,pp.753–756,Sep.1975.

[5] R. G. Hunsperger, “Mg and Be ion implantedGaAs,” J. Appl. Phys.,vol.43,no.3,p.1318,Nov.1972.

[6] W.Wesch,“IonimplantationinIII–Vcompounds,”Nucl.Instrum.MethodsPhys.Res.B,vol.68,nos.1–4,pp.342–354,May1992.

[7] N.N. Gerasimenko, A. M. Myasnikov, V. I. Obodnikov, and L.N.Safronov,“RedistributionofmagnesiuminInAsduringpostimplantationannealing,”Nucl.Instrum.MethodsPhys.Res.,vols.80–81,pp.924–926,1993.

[8] Q. W. Wang et al., “Lattice expansion and evolution of damage buildupin Be-implanted InAs,” Nucl. Instrum. Methods Phys. Res. B, vol. 269,no.21,pp.2527–2531,Nov.2011.

[9] N.N.Gerasimenko,G.L.Kuryshev,A.M.Myasnikov,V.I.Obodnikov,and I. V. Verner, “Distributionof impuritiesimplantedin InSb andInAs before and after annealing,” Nucl. Instrum. Methods Phys. Res. B,vols.127–128,pp.446–450,May1997.

[10] N. N. Gerasimenko, G. S. Khryashchev, G. L. Kuryshev,A. M. Myasnikov, and V. I. Obodnikov, “SIMS study on redistributionofimplantedimpuritiesinInSbandInAsduringpost-implantationannealing,”Nucl.Instrum. MethodsPhys. Res. B, vol. 111, nos. 3–4,pp.281–284,1996.

[11] J.P.BiersackandL.G.Haggmark,“AMonteCarlocomputerprogram for the transport of energetic ions in amorphous targets,” Nucl.Instrum.Methods,vol.174,nos.1–2,pp.257–269,Aug.1980.

[12] E. Wendler, T. Opfermann, and P. I. Gaiduk, “Ion mass and temperaturedependence of damage production in ion implanted InP,” J. Appl. Phys.,vol.82,no.12,p.5965–5975,1997.

[13] A.R.J.Marshall,C.H.Tan,J.P.R.David,J.S.Ng, and M.Hopkinson,“Fabrication of InAs photodiodes with reduced surface leakage current,”Proc.SPIE,vol.6740,p.67400H,Oct. 2007.

[14] J. P. Donnellyand C. E. Hurwitz,“The effectof implanttemperatureon the electrical characteristicsof ion implanted indium phosphide,”Solid-StateElectron.,vol.23,no.9,pp.943–948,Sep.1980.

[15] P.J.Ker,J.P.R.David,andC.H.Tan,“TemperaturedependenceofgainandexcessnoiseinInAselectronavalanchephotodiodes,”Opt.Exp.,vol. 20,no.28,p.29568,Dec.2012.