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Electron Beam Lithography and It's application in Nanoscale Fabrication

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ABSTRACT—Miniaturizationisthecentralthemeinmodernfabricationtechnology.Manyofthecomponentsusedinmodernprod-ucts are getting smaller and smaller. In this paper, the recent de-velopmentoftheelectronbeamlithographytechniqueisreviewedwith an emphasis on fabricating devices at the nanometer scale. Be-cause of its very short wavelength and reasonable energy densitycharacteristics, e-beam lithography has the ability to fabricate pat-ternshavingnanometerfeaturesizes.Asaresult,manynanoscaledevices have been successfully fabricated by this technique. Fol-lowing an introduction of this technique, recent developments inprocessing, tooling, resist, and pattern controlling are separatelyexamined and discussed. Examples of nanodevices made by sev-eral different e-beam lithographic schemes are given, to illustratethe versatility and advancement of the e-beam lithography technique.Finally,futuretrendsinthistechniquearediscussed.

IndexTerms—Directwriting,e beamresist,electronbeamlithography,nanodevices,nanofabrication,nanotechnology,projectionprinting.

I. INTRODUCTION

INIATURIZATIONandperformanceimprovements aredrivingtheelectronicsindustrytoshrinkthefeature sizeofsemiconductordevices.Becauseofitsdiffractionlimit,conventionalopticalorultravioletphotolithographyisbecomingincreasinglyinadequate.Asanexample,eventhe refractive optical lithography is anticipated to reach itslimit at a wavelength of 157 nm, beyond which significantissuesariseintermsofavailabilityoflightsources,masks,and the need for new photoresist materials (SIA, [22]). Otherlithography techniques, which use different forms of radiation,including extreme UV, x-ray, electron beams, and ion beams,to offer higher resolution, are growing in importance. A greatdeal of research has been done on these techniques to scalelithography technology down to the nano-scale arena (Brodieand Muray, [3], Timp, [9]). In this paper, the electron-beamlithography (EBL) technology will be reviewed. The latestdevelopments, including the beam sources, system, process,resist,and application,areexaminedand discussed.

Lithography is the process of transferring patterns from onemedium to another. For many years, particle beams of varioustypes have been used in lithography. The electron source hasthebenefitofextremelyhighdiffraction-limitedresolutionandhas been used for transferring patterns having nanometer fea-ture sizes. Recently they have become the popular selection inmakingnanoscalestructures,bybothdirectwritingandprojec-tion printing techniques. In the semiconductor industry, EBLhas been routinely used to generate master masks and reticlesfrom computer-aided design (CAD) files [7]. These masks areusually used in optical projection printing to replicate the pat-terns on silicon wafers. EBL has begun to find applications indirectwriting,wherethefocusedbeamdirectlyimpingesontheresistinordertoperformvariousactivities. Thedefinitionofnanoscalelithographyherefollowsthatpro-videdbytheUSNationalScienceFoundation,anditcanbein-terpretedasusinglithographictoolsforfabricationofanystruc-tureshavingfeaturesizeslessthan100nm.Nanoscalelithog-raphyisalargecollectionofnano-fabricationtechniquesthathaveoriginatedfromthesemiconductorindustry.Itnormallyre-movesoraddsmaterialonasubstrate,similartoaddingbricksordiggingholestoconstructabuilding.TheplanarprocessesintheICindustryareinherentlybatch-fabricationtechniquesthatenableparallelproductionofalargenumbersofhighlypre-ciseelectroniccircuitsthroughasinglepassofprocessingse-quences.Nanoscalelithographybenefitsfromthesameprecisebatch-fabricationprocessesinthecreationofnanoscaledevices.Inthispaper,thetechnologiesofprojectionprintinganddi-rectwritingarereviewed.Theothertypesoflithography,in-cludingproximityprintingandcontactprinting,arenotincludedinthispaperbecausetheyhaveverylimitedflexibilityandnorigorouseffortshave beenreportedtospecificallyimprovethecurrentsystems.Inthefollowingsection,thepresentstatusofboththeprojectionprintinganddirectwritingsystemsisfirstassessed. The e-beam resists developed for different applicationsarethenexamined;thenewlydevelopedresistsandtheerrorsourcesinpatterninganddimensioncontrolarealsodiscussed.Toillustrateseveralnewlydevelopeddirectwritinglithographytechniques,thenanostructuresrecentlyfabricatedbythesetechniquesandtheirapplicationsarepresentedinsomedetail.Fi-nally,concludingremarksonfuturetrendsofthee-beamlithographictechnologiesaregiven.

II. PROCESS AND SYSTEM

The main advantages of e-beam lithography over the con-ventional photolithograph techniques include very high resolutionandversatilepatternformation.Ingeneral,twodistinct schemes, projection printing and direct writing, are used in EBL.As shown in Fig. 1, in projection printing, a relatively large-sized electron-beam pattern is projected in parallel through themask onto a resist-coated substrate by using a high-precisionlenssystem;indirectwriting,asmallspotoftheelectronbeamiswrittendirectlyontoaresist-coatedsubstrate,eliminatingtheexpensive and time-consuming production of masks. Recent developmentsinthesetwoschemesarepresentedinthissection.

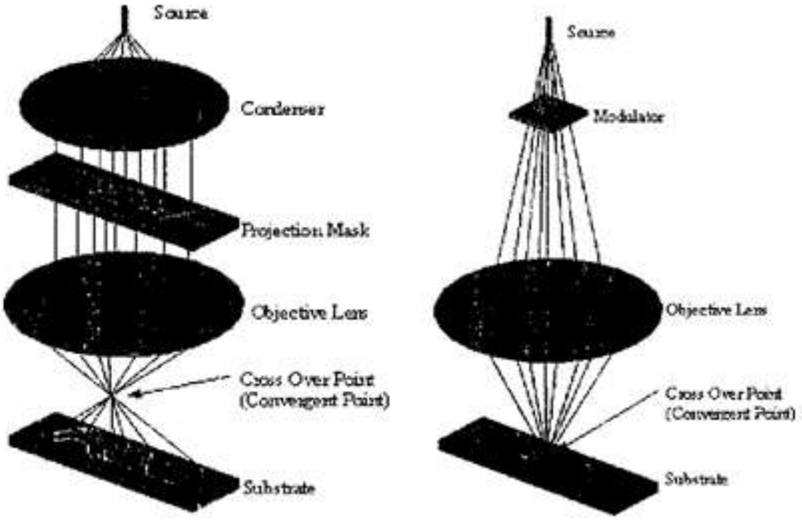


Fig.1.Schematic ofdirectwritingandprojectprinting.

A. ProjectionPrinting

SeveralversionsofprojectionEBLsystemshavebeendeveloped.BellLaboratoriesstartedtheprojectionEBLdevelopmentwiththeinventionoftheScatteringwithangularlimitationinprojectionelectron-beamlithography(SCALPEL)systemin1989[2],whileIBMhadlaidthefoundationforitsprojectionreductionexposurewithvariableaxisimmersionlenses(PREVAIL)technologywiththedevelopmentofthevariable-axislensforelectron-beamlithographysystemsduringthe1980s[17],[18]. Bothconceptsprojectasmallfield imageof amaskonto awafer togenerate nanoscalesubpatterns.

Theshortpenetrationlengthofelectrons,however,precludesthe use of a solid substrate, like quartz, for the mask. A verythin membrane mask can be used; otherwise, a stencil maskwith cutouts through which beams can pass is needed. Thesemaskdifficultiesandotherproblems,includingstitchingagreatnumber of subpatterns into a single overall pattern, the aberrationlimitation,andexcessivethermalabsorptionorexpansion,are sufficient to prevent the projection EBL from being a completelypracticaltoolfornanofabrication.

The strength of SCALPEL, which differentiates it from pre-vious attempts at projection EBL, lies in its specially designedmask,alsoknownasthescatteringmask.TheSCALPELmaskconsists of a low-atomic number membrane, on which a layerofthepatternmadeofahigh-atomicnumbermaterialiscoated.Whentheelectronspassthroughthehigh-atomicnumbermate-rial, they scatter more strongly and at higher angles than thosethat pass through the low-atomic number membrane. As illus-trated in Fig. 2, an aperture located at the back focal plane ofthe projection lens blocks the strongly scattered electrons, whilethosepassingthroughthemembranesufferlittlechangetotheirtrajectories and travel through the aperture. As a result, the un-blockedelectronsthatpassthroughtheapertureformahigh contrastimageprintedonthewaferorsubstrateplane.Thetypical SCALPELmaskisathinnitridefilm(about100nmthick)ontopofwhichathintungstenpattern(50nmthick) isplaced.Since the incident electron energy is not only absorbed by themaskbutalsoblockedbytheaperture,thermaldistortionofthemaskcanbeminimized.

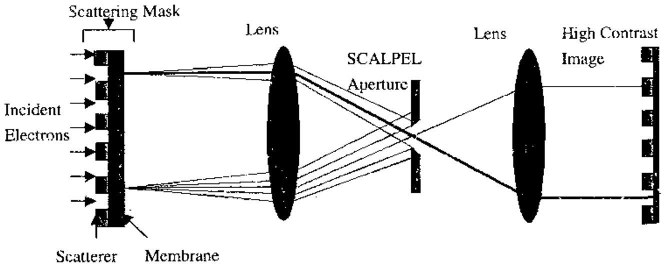


Fig.2.SCALPELprincipleofoperation.

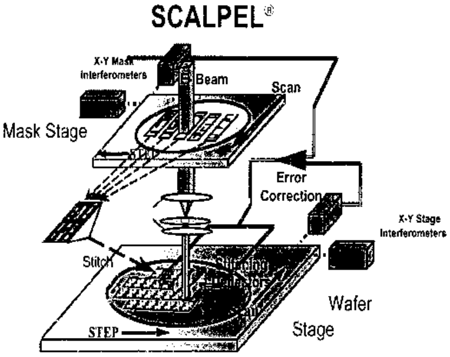


Fig.3.SchematicofSCALPELproof-of-conceptsystem(withpermissionbyLucentTechnologies).

To avoid the excessive distortion by field aberrations of elec-tron optics, the field size of an electron beam that can be pro-jected through a mask on the wafer is kept relatively small, inthe order of 1-mm . The small field size or printing area haspresentedamajorconcerntotheSCALPELsystem. Inordertoimage a full 300-mm wafer, the entire wafer has to be exposedsequentially by stitching these small fields together with highaccuracy. Strict mechanical positioning of mask and wafer to ac-complish field stitching would be limited by stage accelerationand speed, and would result in prohibitively low throughput.Fig. 3 shows a SCALPEL proof-of-concept system developedby Lucent Technologies [12] using the step-and-scan writingstrategyinsteadofthestep-and-repeatschemenormallyusedinphotolithography system. As shown, x-y mask interferometerson the top helps in the positioning of the beam. Below it is themask stage with the pattern. It also shows the focusing lensesandthewaferstage wherethestitchingoperationisshown.Anerror correction module is included in the schematic. Also thedirection of the step and scanis shown in the diagram.

In the PREVAIL approach, the small fields in both reticleand wafer^{2} are stitched through a combination of high-speedelectronic-beamscanningandmoderate-speedmechanicalscanning.ThecornerstoneofthePREVAILapproachisasystem of variable-axis lenses. The variable-axis lens permitsshiftingoftheelectronopticalaxisalongapredeterminedcurvature, while simultaneously deflecting the electron beamtopreciselyfollowthecurvilinearvariableaxissothatthe

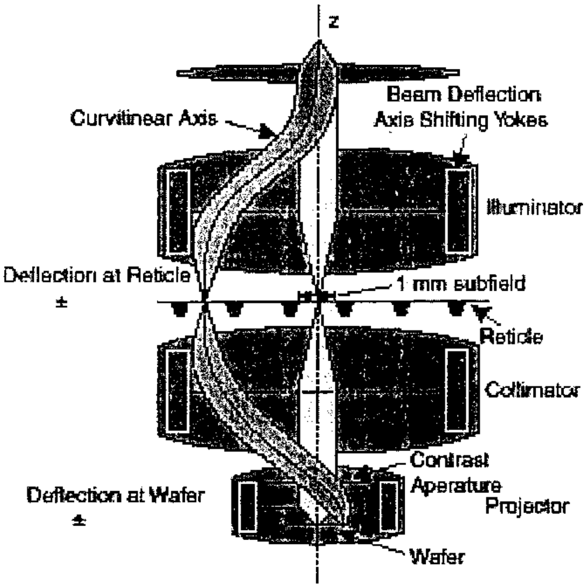


Fig.4.PREVAILimaging conceptconcept[18].

beam effectively remains on the axis, eliminating all off-axisaberrations. This task is performed through the superpositionof various magnetic deflection fields. Fig. 4 shows the basicPREVAILimagingconcept[18].Theilluminator isamagneticlens that system provides illumination for each field pattern byimaging a 11-mm shaped beam onto the reticle. Collimatorand projector lenses form an antisymmetrictelecentric doubletknown to inherently possess minimal geometric aberrations.Thecurvedbeampathschematicallyillustratestheilluminationand imaging of a field at the edge of the optical field of view.Aproof-of-conceptPREVAILsystemhasrecentlyachievedanenhancedfieldsizeorprintingareaof10mm10mm[6]. This result makes the PREVAIL approach promising, butfurther improvement is needed because larger scan ranges arerequired for the illumination and projection of the reticle,and also because the enhanced pattern field (10-mm) is stillordersofmagnitudesmallercomparedtothesizeofthecurrent300-mmsemiconductorwafer. OtherprojectionEBLattempts,includingthemultiplecolumn(orbeam)systemdevelopedbyETEC,anAppliedMa-terials-ownedcompany,areinmuchearlierstagesascomparedwiththestatusofSCALPELandPREVAIL.Thechallengefor all of these emerging technologies is to downscale thefeature size while maintaining a high throughput. To increasethe throughput and the quality of the product, the advantagesoftechniquesusedinSCALPEL,PREVAIL,andmulti-columnsystemswilleventuallybeintegratedintoonesystem.Onceintegrated,theprojectionEBLcanbecomeinthenextgenerationlithography mainstreaminthesemiconductor industry.

B. DirectWriting

Direct writing is the most common EBL approach. Derivedfrom the early scanning electron microscopes, the direct writingEBL has been used for a variety of applications since the late1960s and many commercial systems have been developed sincethen. Normally, the direct write systems use a finely focusedGaussianroundbeamthatmoveswiththewafer toexposethe wafer one pixel at a time, and can be classified as raster scansor vector scans, with either fixed or variable beam geometry.Basically,asshowninFig.1,adirectwritingsystemconsistsofasourceofelectrons,afocusingopticsset,ablankertoturnthebeamonandoff,adeflectionsystemformovingthebeam,andastageforholdingthesubstrate. ThedirectwritingEBLcanbeusedforgeneratingextremelyfine patterns; in fact, when combined with etching and depo-sition processes, fabrication of future electronic devices withcritical dimension as small as 10 nm has been demonstrated[11]. Since direct writing EBL is capable of superior resolution and requires no expensive projection optics or time con-suming mask production, it is the most desirable process for cut-ting-edge micro and nano-fabrication. However, direct writingtransfers the pattern by exposing one pixel or one image elementatatime.Thisimposesalimitationontheexposure speedor the rate of the pattern to be transferred onto the wafer. Thisthroughput handicap has confined the direct writing system toa supporting role in the semiconductor industry; it has applicationsinfourniches:maskmaking,prototyping,fabric ationofsmall volume special products, and research and developmentforadvancedapplications[13]).

Recently, considerableefforthasbeendedicated to thevariableshaped beam technology to increase its throughput by enhancingexposurespeedandtowidenitsapplicationsbyintegratingwithother nanoscale processes. The shaped beam system uses parallelelectronbeamstowriteaprimitiveshape(mainlyrectangles)inoneshot.Theseprimitiveshapesaresmallerthanthefieldsizesachieved in the projection EBL systems mentioned earlier. In theshaped beam system, the upper aperture in the optics is typicallyusedtoformtwosidesofarectangle,andtheoverlayof theloweraperture constructs the other two sides. More complex shapes canbe achieved by splitting the rectangle before the exposure. Theshapedbeamsystemgainsthespeedorthroughputbycompro-mising the resolution achieved by the single pixel of the Gaussianbeamsystem.

In spite of sizable enhancements, the throughput of shapedbeamsystemsintermsofwafersperhourhasactuallydeclined;thisisduetothecontinuallyincreasingdensityandcomplexityof ICs and expanding wafer size [17]. Since the shaped beamtool is more complicated than the fixed spot (Gaussian beam)system,thetrade-offbetweenpatterngenerationflexibilityandresolution with pattern writing speed will be a major concernforfuturedevelopmentoftheshapedbeamtechnology.Itisbe-lieved that Gaussian beam direct writing will still play a majorrole in nanofabrication because of the continuing shrinkage ofdevices and its combined superiority in flexibility, resolution,precision,andcost.

C. Lift-Off Processand Others

The most popular process used in direct writing EBL is thelift-offprocess;itisanadditiveprocessthataddsmaterialtothesubstrate. The lift-off process consists of several steps: e-beamresist coating, exposure, and development. The normal lift-offprocess is schematically explained in Fig. 5. The top figure[Fig. 5(a)] shows that the resist coating is exposed by e-beam directwritingusingavectororrasterscan,whileFig.5(b)showsthattheexposed resist(thenanostructure pattern)isdeveloped andremovedinasolvent.Ametallayer(thenanostructurema-terial) can be deposited by an e-gun or an evaporation processontothesubstrate,asdepictedinFig.5(c).Thefinalstepoftheliftoffprocessisaccomplishedbysoaking thesubstrateina solvent bath (e.g., acetone for PMMA resist) to wash awaytheremainingresistandunwantedmaterial.Thefinaldepositednanostructureon asubstrateis showninFig. 5(d).

Frequently, the liftoff process prefers a thick resist layer forformingundercutprofilesandgoodadhesionwiththesubstratefor the subsequent additive or subtractive

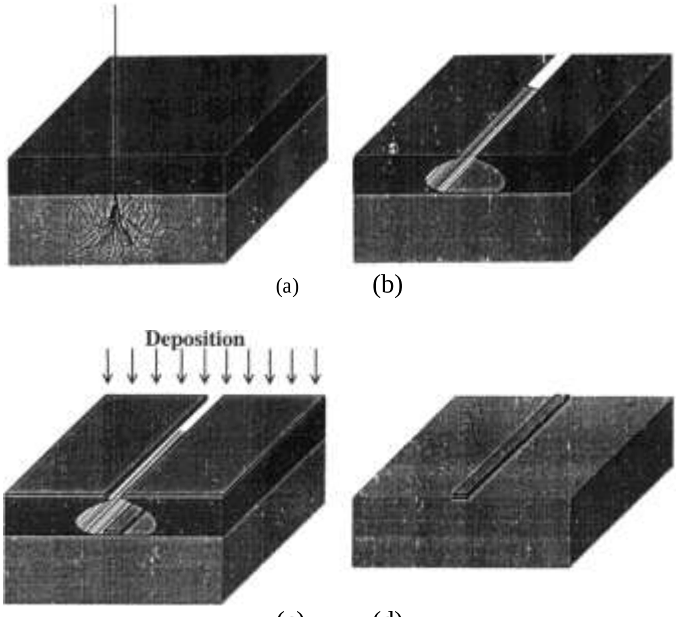


Fig. 5.Schematic of EBL liftoff process: (a) electron beam injection withscattering,(b)exposedresistdevelopedandremoved,(c)depositionofdesiredmaterialsbye-gunorvacuumevaporation,and(d)liftoffofunwantedmaterials.

processes. Since theseetching or deposition processes are very similar to those in theconventional photolithography process, their procedures and re-quirements can be found in most semiconductor processing textbooksandarenotrepeatedhere.

III. E-BEAMRESISTS

Electronbeamresistsarenormallycoatedonthesubstrateto record the image of the pattern to be transferred. The finalpattern made by the EBL is a relief structure in the coated resistlayerrepresentingthepatternbeingexposed.Inthissection,a few standard resist systems will be presented. Some usefulrecipescanbefoundinensuingsectionswherethe fabricationsof specific nanostructures are presented. In depth reviews of thissubject can be found in Reichmanis and Novembre [19] and HelbertandDaou[8].

Usually, the e-beam resists are high molecular-weight poly-mers dissolved in a liquid solvent. The polymer changes itsstructure when exposed to radiation, including electron radia-tion. Electron beam resists can be either positive or negative.After exposure to electrons, the positive resists are weakenedbythescissionofmain-andside-chainsandtheexposedresistsbecome more soluble in the developing solution. A solvent developerselectivelywashesawaytheweakenedorlower molec-ular-weightresist; thus,a positivetonepattern isformedin the resist film. On the other hand, the negative resists are strength-ened during exposure by a radiation-initiated cross-linking re-action and become less soluble in the developer. After the resistsaredeveloped,thepatternistransferredtothesubstratethroughthelift-offprocessmentionedearlier.

A. PositiveResists

Polymethyl methacrylate (PMMA) was one of the first resistsdeveloped for EBL and remains the most commonly used positiveresistthathasamoderateglasstransitiontemperatureof 114C. The PMMA comes in powder form and is dissolved inasolvent,suchasanisoleorchlorobenzene,ofdesired concen-tration. The resist liquid is dropped onto the substrate and thenspun at high speed to form a thin coating. This is followed bysoft bake processing at temperatures ranging from 130C to170 C with a hot plate or oven to bake out the casting solvent.The final resist thickness is determined by the PMMA concen-tration and by the spin speed. For instance, 950 K PMMA (2%in anisole) resist spun at 3000 rpm would result in a thicknessofabout200nm.Thedosevaluesoftheelectronbeamusedforexposure range from 100 to 500C/cm[Fig. 5(a)]. The typ-ical developers used are 1:3 methyl isobutyl ketone: isopropanol(MIBK:IPA)forthehighestcontrastand1: 1MIBK:IPAforthehighest sensitivity [1]. The developed region is then removed byrinsinginpureIPAfor30s.

PMMAhasextremelyhighresolution,anditsultimateresolution has been demonstrated to be less than 10 nm [11];its major problems are its relatively poor sensitivity, poor dryetchresistance,andmoderatethermalstability.The copolymer,Methyl MethAcrylate and MethAcrylic Acid [P(MMA-MAA)],provides a three- to four-fold improvement in sensitivity rel-ative to PMMA and image thermal stability of 160C. SinceP(MMA-MAA) can also be developed in MIBK:IPA solventas used for PMMA, a single-step development of mixed layersof PMMA and P(MMA-MAA) is possible for enhancing thesensitivity and thermal stability of the resist. Other importantpositiveresistsincludePBS(PolyButene-1-Sulfone)andEBR-9(acopolymeroftrifluoroethyla-chloroacrylateandtetrafluropropyl a-chloroacrylate) which have high sensitivityandZEP(acopolymerofchloromethacrylateandmethyl-styrene) which has high-resolution. It is noted that the desiredproperties of a resist are high resolution and high sensitivity(high speed). Unfortunately, the resist that have higher sensitivity, including those mentioned here, usually have lowerresolution,especiallycomparedtoPMMA.

B. Negative Resists

Negativeresiststendtohavelessbiasbuttheyhaveproblemswith scum and swellingduring development andbridgingbetweenfeatures.Popularnegative e-beamresistsconsist of the Shipley advanced lithography (SAL) productline, an epoxy copolymer of glycidyl methacrylate and ethylacrylate [P(GMA-EA)], also known as COP, and a partiallychloromethylatedpolystyrene(CMS).Also,PMMAcanexhibitnegative tone when exposed to a dose one order of magnitudehigher.WhileCOPhashighsensitivity,CMSpossessesmodestresolutionatmodestsensitivity.

The SAL offers many new deep-ultraviolet (DUV) resiststhroughtheuseofchemicallyamplified(CAP)resistmaterials.FastversionsofCAP,suchasSAL601-ER7(anegativeresist)have demonstrated high-resolution capability with 100 nm linesatasensitivityhigherthanPMMA.TheuseofDUVresistsinEBLalsoopensupthepossibilityofexposingthesameresistlayertobothDUVsteppersandEBLmachines beforedevelopment,sothatlargeareascanbeexposedw ithmedium-to-low-resolutionby the fast DUV stepper, whereas the high resolution details canbe exposed by the accurate but slow EBL. This approach, alsoknownasmixandmatchtechnology,canachievethehigh-resolutiondetailincriticalareasbutrequireslessexposure time.

IV. PATTERN VARIATION

The electron de Broglie wavelength of a typical EBL operatingcondition,50keV,islessthan10pmor0.01nm,whichisfar below typical atomic sizes. Hence, diffraction is not a limitingfactoroftheresolution.Ideally,e-beamdiametersarepos-sible on the order of 1 nm. However, beam-material or scatteringinteractiondegradesthislimitsignificantly[16].

A. ScatteringorProximityEffect

When theelectron beam strikes theresist solid, many ofthe electrons experience small-angle forward scattering, whichtendstoenlargetheinitialbeamsize.Astheelectronspenetratethrough the resist into the substrate, some of them undergolarge-anglescatteringeventsleadingtobackscattering,inwhich these electrons return back through the resist in a regionfar from the desired exposure. This causes additional exposurein the resist and is also known as the e-beam proximity effect.Also,astheprimaryelectronsslowdown,muchoftheirenergyisdissipatedintheformofsecondaryelectronsinwhichasmallportion may have significant energies, on the order of 1 keV.These so-called fast electrons are responsible for the bulk ofactualresistexposureandcancontributetotheproximityeffectintherangeofafewtenthsofamicron[13].

B. Remedy

The net results of scattering electrons cause the dose deliveredby the e-beam not to confine to the original shape, resulting inpattern variations. Thus, many different approaches have beendeveloped to alleviate the proximity effect or minimize patternvariation.Somesimpleremediesincludeusingathinresistthatis less than the feature size or a thin coating between the resistand the substrate to partially “filter” the secondary and somebackscatteringelectrons.

The most systematic way is dose control. Different featuresizes have different dose requirements. If the pattern is uniform,the overall dose is simply adjusted until the desirable patternsize is achieved. If the pattern is rather complex, dose modu-lation should be considered. The specific dose assignments areoftenmadeatfracturetimebyfilteringshapeaccordingtosize,andcanbeplacedonseparatedatafilesintheCADtoolusedinEBL.CommercialCADtools,suchasSELIDandCAPROXbySIGMA-C,andPROLITHbyKLA-Tencor,havebecomeavailable for simulating e-beam exposure, as well as for correctingtheproximityeffect[5],[15].

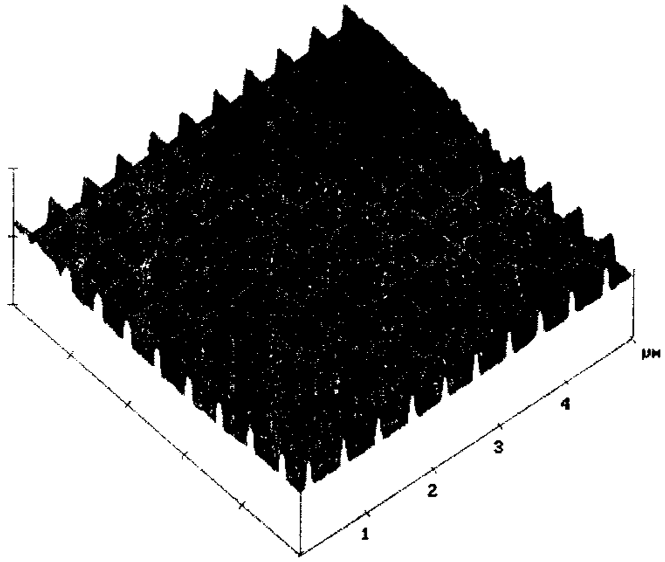


Fig. 6.AFMImageofEBLfabricatedAu-Mesh.

Other error sources for pattern variations include the pathbuttingerror,resolutionoftheresist,nonuniformresisttemper-ature, beam current instability, spot size instability, and beamdeflectionerror[10].

V. FABRICATION

The fabrication processes for making four nanostrutures arepresented in this section to illustrate the standard and nonstan-dardlift-offtechniquesaswellastheapplicationsinvolved.

A. Nano-MeshPattern

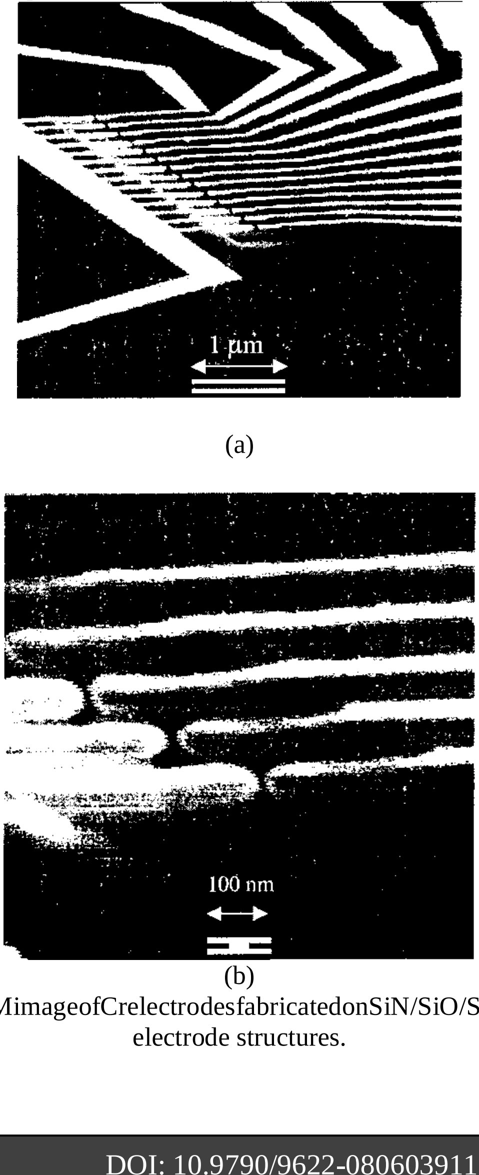
A gold mesh pattern on a silicon substrate used for calibrationofatomicforcemicroscopesisfirstpresentedtoillustrateananostructuremadebythestandardlift-offprocessdescribedinFig. 5. The mesh pattern is designed in a CAD program and isloaded into the control system of an electron beam writer, normallycontrolledbysoftwareloadedonaPC.

The Si substrate is coated with a 200-nm thick PMMA re-sist and an area dose of 250C/cmis used for exposure. Theexposed region is then developed and removed. After devel-oping, the sample is also subjected to an oxygen plasma cleaningprocess (85 mTorr, 40 W, 45 s) to ensure a residue-free image.Gold is then deposited from a small source onto the substrateandresistbythermalevaporation[Fig.5(c)].AnAFMimageofthe fabricated mesh pattern is shown in Fig. 6. Both the widthand height of the mesh line are 40 nm, while the mesh linespacingisapproximately500nm.

It is noteworthy that because of the backscattering of elec-trons mentioned earlier, the lower part of the resist receives moredosage than its surface, resulting in a slightly undercut profilealongtheedgesofthepattern[seeFig.5(b)].This undercutprovidesacleanseparationofthedepositedmaterialand,hence,asharpliftoffpattern.

B. NanoBimetal-Electrodes

The lift-off process can be combined with other nano-processestomakecomplexdevices.Manufacturingofanarray



(a)

(b)

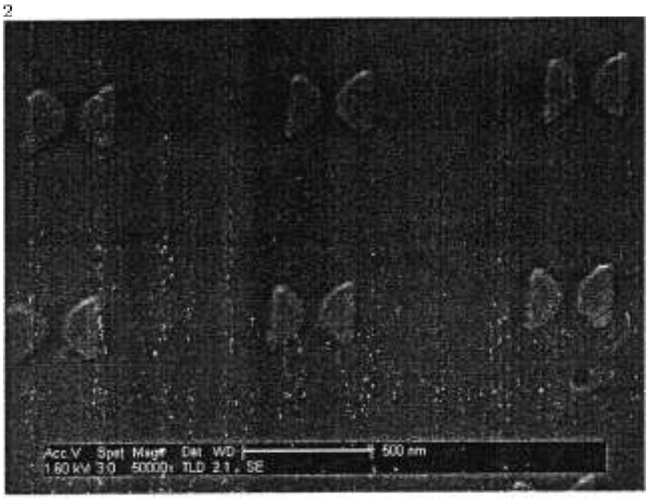
Fig.7.Nano-electrodePairs(a)SEMimageofCrelectrodesfabricatedonSiN/SiO/Si-substrateand(b) enlargement of electrode structures.

ofnano-scale electrode pairs is presented in this subsection.Fig. 7(a) shows a scanning electron microscope (SEM) pic-ture of the resulting nano-structure; the two oppositely pointedAu-electrodes[Fig.7(b)],actingassourceanddrain,consist ofa 10 nm-thick Cr bottom layer, which is used as an adhesionlayer, and a 25 nm-thick Au top layer. The width of the elec-trodes is about 160 nm, and the spacing between them is 400 nm.Thegapbetweentheelectrodetipsisabout15nm.ThetwoAuelectrodesaremaderelativelywidersoastosustainthemselveswithoutasubstrate.

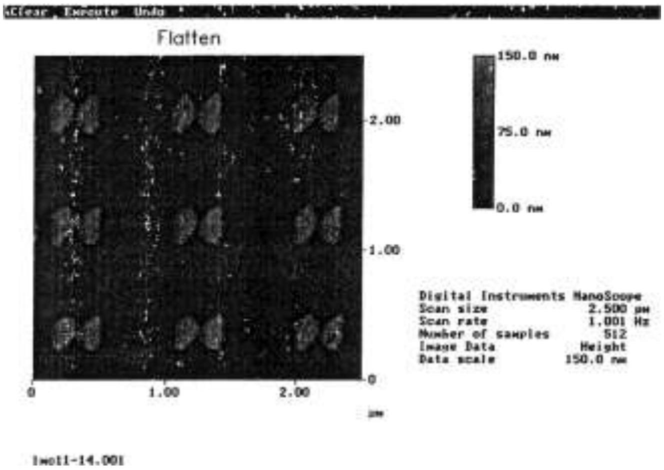
The substrate isastandardSi wafer coveredby a 100nm-thickLPCVD-grownSi_3N_4 anda300nm-thickthermallygrownSiO_2layer.AwindowontheSi_3N_4/SiO_2layerbeneaththegapisdefinedbythelift-offprocessandaccomplished by CF_4/O_2plasma reactive ion etching of Si_3N_4layerandHFwetetchingofSiO_2 layer.TheunderlyingSi_3N_4/SiO_2areetchedouttoformawindowsothattheappliedelectricfieldbetweenelectrodetipscanbehighlyconcentrated.Nanoparticlescanbeallocatedinthegapbetweentheelectrodetipsusingaself-assemblyprocess,whichfollowsthisstageoffabrication[21].

C. Non-ConductingSubstrateUsingBilayerResist

TheEBLprocessusingabilayerresistforabowtiestructureonaninsulatingsubstrateispresented.Thelithographysystem



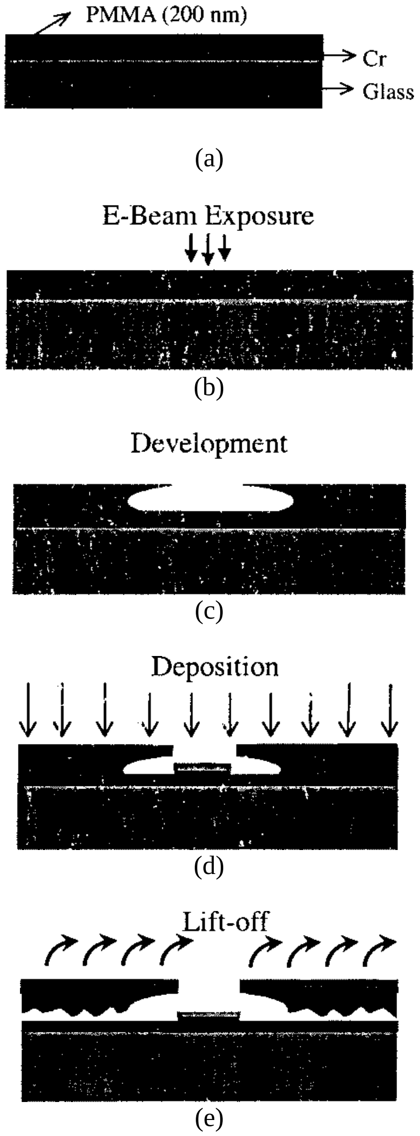
(a)

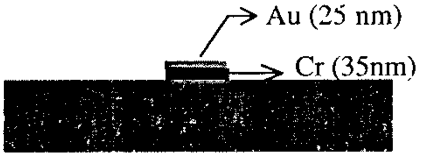


(b)

Fig.8.Bilayernano-bowtiestructuresonaglasssubstrateusingbilayerresist: (a)SEMimageand(b)AFMimage.

usedisconvertedfromHitachi54200scanningelectronmicroscopeusingavactorscanprocedure.Thebowtiestructureisamajorcomponentofanext-generationopticalprobe.Theopticalprobeisbasedonaconcept,calledthewaveinterrogatednear-fieldarray(WINFA),whichcombinesthesensitivityofnear-fielddetectionwiththespeedofopticalscanning[14].Itisexpectedthatbowtieshavinga40-nmgapshouldactasresonantelementstoprovidespatialresolutionwellbelowtheopticaldiffractionlimitwiththetransmissionefficiencyapproachingunity.Thefabricatedbowtie-structureisdesignedfortheincidentsourcehavingawavelengthintheneighborhoodof500-nm(greenlight)sincetheilluminatedorgapareaisapproximatelyoneeighthtoonetwelfthofthesourcewavelength.Itisexpectedthatvoidsorparticles50-nminsizeorsmallercanbeidentified.Asadesignrequirement,thesubstrateofthebowtiesshouldbetransparenttotheincidentwavesource,andthus,aglass-basedsubstrateisused.However,whenpatterninganinsulatingglasssubstrate, thesubstratechargingcausesconsiderabledistortion.Tocopewiththedistortionproblem,alsoknownasthedischargeaccumulation[13],abilayerresistisusedinEBL.ThebilayerresistconsistsofaconductinglayersandwichedbyapolymerresistlayerandthesubstrateSubstrate,whichisusedtoeliminate





(f)

Fig.9.Liftoffprocessusingbilayerresist:(a)depositCrandspin-coatPMMA, (b) patterning, (c) creating undercut in PMMA, (d) depositing 5–nmCr and 25–nm Au, (e) removing unwanted materials, and (f) wet etching withAuasmasktoremoveunprotectedCr.

the charge accumulation problem. Fig. 8(a) shows a SEM imageof the bowtie array fabricated on a 0.5-mm-thick Pyrex glasssubstrate; the gap of the fabricated bowties can be observed tobeapproximately40nm.

To prepare the bilayer system, a 30-nm thick Cr film is firstcoated on the Pyrex glass substrate by thermal evaporatingprocess. Then a PMMA resist film is spin coated to cover theCr layer [Fig. 9(a)]. As the pattern is defined on this top layer,a thinner film is preferred, as it would produce a better patternsharpness. A diluted PMMA resist (2% in anisole), spun at 3000rpm,isused.Aftersoft-bakingat135 C,athin(nm)PMMAresistfilmisformed.Thebilayerresististhenexposedwithanareadoseofapproximately250C/cm[Fig.9(b)].The

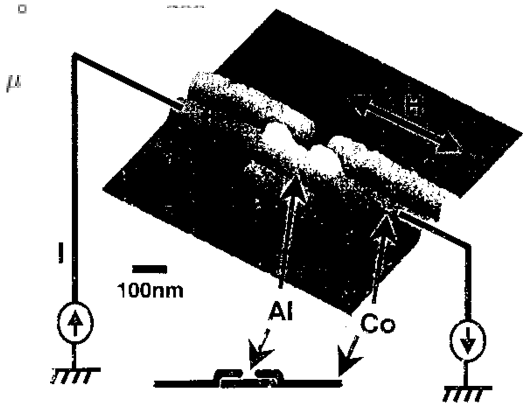


Fig.10.AFMimage of FM/SC/FM transistorandbiasing circuit.

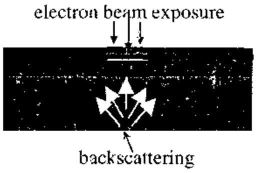
exposed region is developed, removed, and cleaned to insure aresidue-freeimage[Fig.9(c)].A5-nmCrisdepositedfirstwhilea 25-nm Au is then deposited [Fig. 9(d)]. The unwanted materialsareliftedoff[Fig.9(e)].TheAulayerthenactsasamaskwhilethe unprotected Cr is removed by the chrome wet etching process[Fig. 9(f)]. A relative thick structure can be formed by the bilayerresist technique because the structure consists of two layers. ThecorrespondingAFMimageofthebowtiesisshowninFig.8(b).The thickness of the bilayer bowtie can also be estimated fromtheimageisaround60-nm;ithasa25-nmAulayerontopofa35-nmthickCrlayer.

In addition to making a thick structure, the bilayer resistschemeisnotonlytocopewiththechargeaccumulationproblemcausedbyanonconductingsubstratebutalsotoeliminate the “lift-off flag” defects in which thicker materialsappearalongthebowtieedgeswhenthestandardorthesingle-layer-resistlift-offprocessisemployed.

D. TandemPatternbyTri-LayerResist

Spinimbalancecanleadtosuppressionofsuperconductivity.Aferromagnet-superconductor-ferromagnet(FM/SC/FM)single-electrontransistorhasbeendevelopedtousespinimbalance to effectively suppress the gap superconductivitywith the goal for better control of its superconductivity at lowtemperatures within low fields [4]. The FM/SC/FM doubletunneljunctionsaremadeofthecorrespondingCo/Al/Colayers.Thesuperconductinggapsuppressioncanbeturnedon and off by manipulating mutual orientations of magneticmoment of the two Co leads. The effects of the suppressionincreaseswithincreasingsource-drain.Thesingle-electrontransistor(SET)isapotentialcandidateforthenextgenerationof electronic devices because of its great advantages in lowpower consumptionandhighpackingdensity.

Fig.10showanAFMimageanditsbiasingcircuitofthe Co/Al/Co transistor, while Fig. 11 is the correspondingmagnetic force microscope (MFM) image obtained using lowmagnetic stray field and high coercivityCoPt tips. The inset inFig. 10 illustrates the cross section of the island and junctions.AsshowninFig.11,theCoandAlelectrodesareindicatedby solid and dashed lines, respectively. As shown, these twoelectrodes are similar in shape and run parallel with each otherat50nmapart.Asaresult,thetwoelectrodescanbefabricatedbyonemaskusingatri-layerresist.



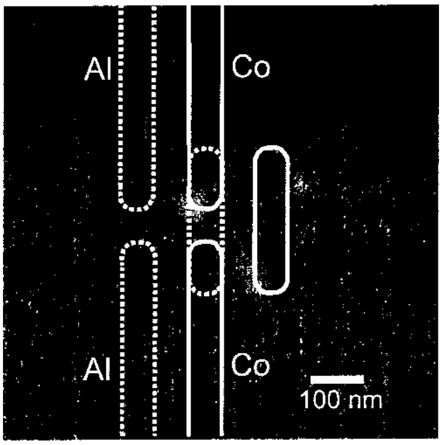


Fig.11.MFMimageofCo(solidline)andAl(dashedline)electrodesinFM/SC/FMtransistor.

Inpreparationofatri-layerresist,athickbottomlayeroftheP(MMA-MAA)resist,actingasaspacer,isspuncoatedonthesubstrate and baked dry as shown in Fig. 12(a). With a coatingspin speed of 4000 rpm and a baking temperature of 165C,theobtainedresistfilmisabout400nmthick.This filmisthencovered with a 20 nm thick thermal-boat evaporated Ge layer.Ge is a good candidate not only for its conducting ability butalso for its small granular size, allowing the generation of finepatterns.ThetoplayerofPMMAresistfilmisthenspincoatedtocovertheGelayer.Asthepatternisdefinedonthistoplayer,a thinner film is preferred, as it would produce better patternsharpness.Tothisend,adilutedPMMAresist(2%inanisole),spun at 5000 rpm, is used. After soft-baking at 135C, it forms athin (100 nm) resist film. The trilayer resist is then exposed withanareadoseofapproximately250C/cm[Fig.12(b)],andthetopPMMAresistisdevelopedin solutionfor 1 minute, rinsed in IPA for 30 s [Fig. 12(c)]. The image isthen transferred to the Ge layer underneath using a CFplasmaetchprocess[Fig.12(d)]. Sincethepatternisdefinedbythethinresistlayerofthehighresolution PMMAonthetopwhiletheheightandundercutareprovided by the thick layer of high sensitivity P(MMA-MAA)on the bottom, the resulting undercut of the pattern can be solargethatitcanallowanarrow-separatedtandempatterns(twoparalleled electrodes) to be formed. The germanium interlayernot only serves as a barrier to separate the top and the bottompolymerlayersbutalsoactsasanexcellentmask forthesubse-quentdepositionprocess.

InpatterningthebottomresistasillustratedinFig.12(e),thesubstrate has to tilt slightly to allow for the creation of a largerandthickerundercutalongthepatternedge.Using twoevaporationsatdifferentincidenceangles,theCoandAlelectrodescanbe separately patterned on the substrate as shown in Fig. 12(f);the distance between the two electrodes shown in Fig. 10 orFig. 11 is approximately 50 nm. If the incidence angles can becontrolledwithhighprecision,thetwoelectrode-structurescanbeshiftedtothedesiredlocationstoformsmalloverlapregions(thetwo hillsin Fig.10 andtheinsert),whichactasthesourceanddraintunneljunctions.Thetransistordevicepresentedhereis similar to that produced by Chen, et al., [4]. As shown, theEBLprocessusingatrilayerresistisparticularlyconvenientfor

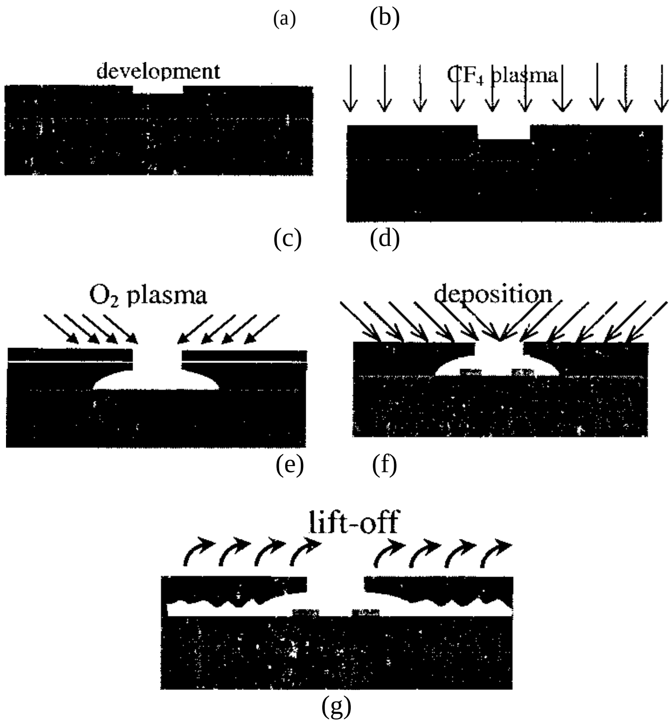


Fig. 12.Liftoff process using trilayer resist with two-angle evaporation: (a)trilayer resist on glass substrate, (b) resist exposed by electrons, (c) devolopedportion removed, (d) etched by CF_4 plasma, (e) oxygen plasma patterningwithatiltedsubstrate,(f)twoseparatedstructuresbytwoevaporations,and(g)lift-offofunwantedmaterials. fabricating two identical patterns where the gap of these twopatternscanbeextremelysmall, at theorderof 10 nm.

VI. CONCLUSION

The current development of electron beam lithography innanofabrication has been reviewed. Both the technologies ofdirect writing and projection printing are examined. A widevarietyofequipmentisavailableforperformingtheEBL.While the equipment for projection printing is still largelyunder development, the direct writing approach is a maturetechnologythatrangesfromafinely-focusedGaussianspotto a complex shape determined by different arrangements ofapertures. Operating conditions also vary widely by changingthe parameters, including beam energy, beam current, and beamdeflectionrate.Moreover,somemachineswritewithstationarysubstrates, while others move the substrates. As a result, thepatterns on the substrate or the fabricated nanostructures aresignificantlyaffectedbytheseparametersandthedesignoftheequipment.

The direct writing EBL has been the most flexible system inmakingavarietyofnanodeviceswithcriticaldimensionsbelow10 nm. The direct writing approach will continue to play a majorrole in nanofabrication and be the de facto technique in maskmaking for other advanced lithographic processes. The versatilityofdirectwritingisalsodemonstratedonfourdifferent nanostructures created by the different EBL processes in thispaper.

On the other hand, by considering the throughput, the projectionprintingEBLshouldhavepotentialtobethemost prob-able method among the next generation lithography (NGL) tech-niques for the semiconductor industry, although the prototypesystems reviewed have indicated that further fine-tuning and im-provement in their resolution and precision are needed. Particularly,theaccuracyofthestitchingschemerequiresfurtherre-fining, and resists with higher sensitivity and better processingcharacteristicsneedtobedeveloped.Itisalsocriticalthat,pro-jection EBL should demonstrate the system level requirementsto be included in the next generation lithography in the semiconductorindustry.

Theprocessesforfabricationoffournanostructuresare specifically presented for illustrating the versatility of directwritingEBL.Theillustratedapplicationsofthese nanos-tructuresinclude calibration, electronics devicesand opticscomponents. A wide variety of other applications, from ma-terials to energy and from cosmetics to health care, all lookpromising [20]. Nanofabrication will be a key technology inthe 21st century and will have a revolutionary impact on everyaspect of the manufacturing industry. Tremendous challengesandopportunitiesawaitforustoexplore.

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