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Ion beam enabled nanoscale fabrication, surface patterning, and self-assembly FREE

Special Collection: Ion Beam Enabled Nanoscale Fabrication, Surface Patterning and Self-Assembly

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INTRODUCTION

Papers in this special topic collection review many aspects of the current status and understanding of nanoscale fabrication, based on newly available insights and instrumentation. These papers review remarkable fundamental and technical advances that suggest promising future prospects. The articles in this section include "Ion-induced nanopatterning of silicon: Toward a predictive model," by Scott A. Norris and Michael J. Aziz;[1] "Prediction of ion-induced nanopattern formation using Monte Carlo simulations and comparison to experiments," by Hans Hofsaess and Omar Bobes;[2] "Cluster beams, nano-ripples, and bio applications," by Noriaki Toyoda, Buddhi Tilakaratne, Iram Saleem, and Wei-Kan Chu;[3] and "Ion irradiation of III-V semiconductor surfaces: From self-assembled nanostructures to plasmonic crystals," by M. Kang and R. S. Goldman.[4]

GENERAL COMMENTS

Intrinsic spatial resolution and the wide available range of ion species, energy, fluence, and beam geometry offer unique options for nanoscale fabrication of structures, patterns, and tailored 3D features, which can enable significant advances in plasmonics, biosensors, semiconductor devices, selective tissue therapy, and other advancing fields.[5,6] Tools now available or under development support beam writing/lithography with <1 nm beam size, cluster ion beam irradiation, surface irradiation systems to promote self-organized patterning, and high energy, high-brightness ion sources for 3D targeting.

NANOPATTERN FORMATION AND MODELING

Essential for future creative new applications of ion beam techniques is a comprehensive understanding and predictive modeling of the complex ion beam–solid interactions, including not only the path of a single ion entering a pristine material but also the changes of host material that will affect the behavior of ions that arrive subsequently or concurrently. Of practical importance is evidently the ability of a broad beam of ions at oblique incidence to promote the development of a self-assembled pattern of surface ripples or dots, suggesting possible applications in patterned optical surfaces, or direct fabrication of nanoscale devices. These topics are reviewed in detail in the papers by Norris and Aziz[1] and by Hofsaess and Bobes.[2]

A completely different set of interactions occurs when a gas cluster ion (an aggregate of weakly bonded gas atoms or molecules), moving with an energy of 30 keV, strikes a planar sample surface, causing multiple simultaneous low energy collisional events with the host atoms and structure. One surprising result is the observed evolution of self-organized surface ripples, similar to those found for simple monomer ion beams. The underlying phenomena are discussed in the review by Toyoda *et al.*,[3] which also reports applications for such tailored surface roughening in the fabrication of biosensors.

Self-assembled orderly arrays of nanoscale features may also be initiated by irradiation of the surface of compound semiconductor surfaces, using Ga ions at energies of many kilo-electron volts, where the resulting preferential sputtering yields a self-assembled periodic array of compositionally changed material, leading to nanoparticle arrays that are valuable for studies of plasmon-enhanced optoelectronics. This topic is reviewed in detail in the paper by Kang and Goldman[4] in this collection.

ADDITIONAL COMMENTS ON THE STATUS OF RELATED FIELDS

Ion beam lithography

One simple motivation for developing processing techniques having few-nanometer fidelity was to re-enable Moore's law for robust commercial manufacture of complex devices that surpass the once-elusive performance criteria of the older semiconductor industry roadmap. This would require patterning with subnanometer fidelity, either via a photoresist protocol or by direct ion beam writing, to locally modify the device material itself. Focused beams of energetic ions (such as those used in FIB etching and imaging) would penetrate the material, leading to complex consequences including lateral spread. To enable sharper focus and avoid the need for serial writing with a scanned beam, a projection ion beam system was developed,[7] in which a large transmission mask would deliver concurrently an entire pattern of ion beamlets to be optically demagnified by a large factor in transit to the receiving surface. Ultimately, this was not pursued by its inventors.

More recently, a robust instrument was developed[8] that delivers a low energy beam of He or Ne ions, with a spot size smaller than 1 nm. This was demonstrated to enable patterning of features with a resolution of a few nanometers in standard photoresists such as HSQ or PMMA.[9] The instrument is now commercially available (Carl Zeiss Orion^{TM} Nanofab), with multiple beams (He and Ne, 15–40 keV). This tool also supports programmed pattern writing (ELPHY) when coupled with a laser interferometer scanning stage (IonLine, available from Raith, Inc.[10]).

The ion beam current available from these instruments is nominally 1 pA or less. While this is excellent (and unique) for research applications, it may not be practical for device manufacturing purposes—especially due to the unavoidable shot noise when drawing a line. Further, the response of standard photoresists to these beams is depth dependent, and the recently recognized intrinsic inhomogeneity of these resists themselves constitutes a further serious barrier to adoption of these tools for device manufacturing that requires fidelity of a few nanometers.

Focused energetic ion beam applications

In some important applications, it is most interesting to modify the chemical state of a target layer or film in a well defined column perpendicular to the surface, without causing significant structural damage to the surrounding material, or surface sputtering, such as might result from collisional displacements of atoms in the host material. This can be achieved by using light ions at high energies up to several mega-electron volts, whose energy transfer to the target material is mainly from electronic (ionization) processes. In the absence of collisional events, the ion trajectory through the solid is straight. For protons at mega-electron volt energies, the rate of energy deposition along most of the ion path is only weakly dependent on depth.

In such cases, a tightly focused ion beam can be used to affect a correspondingly well defined space. A pattern drawn with such a narrow beam can be free from significant proximity effects that often degrade writing done with heavier ions and lower energies.[11]

Potential future applications of this approach include not only high resolution writing but also localized deterministic ion implantation for fabrication of quantum devices[12] and targeted tumor therapies. Practical applications will depend on the development of new high-brightness ion sources, having beam resolution of a few nanometers and providing beam currents sufficient to support commercial adoption. Initiatives in this field are currently in progress.[13]

SUMMARY

New ion beam technologies are now available for realistic applications in nanoscale engineering and research. Their scope is remarkable, and prospects for further insights and understanding and practical advances are compelling.

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