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A Theoretical Study of 30 to 50 Angstrom Noble Gas Heavy Ion Lithography

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ABSTRACT

The feasibility of using heavy noble gas ions to etch 30 to 50 Å wide lines in polymethylmethacrylate (PMMA) on a silicon substrate was investigated. The TRIM91 computer code was used to model point sources of neon, argon, xenon, krypton, or uranium ions penetrating a two-dimensional geometry consisting of a 50 Å layer of PMMA over a 50 Å layer of silicon. For ions with a kinetic energy less than 500 eV, the energy deposition is so confined that the proximity effect is virtually nonexistent. These and other considerations indicate that heavy noble gas ions may be ideal for etching angstrom-level features in this geometry.

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INTRODUCTION

Recent studies by Bell labs and others have shown that ion lithography has advantages over x-ray and electron lithography for etching angstrom-level features in polymethylmethacrylate (PMMA) on a silicon substrate. The principal considerations, from a physics viewpoint, are the brightness of the incident beam, the resolution of the beam, and the sensitivity of the resist. The beam brightness is a function of the source; ways to optimize the brightness of an ion source are discussed by K. Horiuchi and colleagues.[1] The TRIM91 code[2] we used models a point source that has constant brightness, so the issues we investigated are:

1. The relative sensitivity of the resist, and

2. Optimal resolution capabilities among ions, electrons, and x-rays.

PHYSICAL CONSIDERATIONS

T. M. Hall and colleagues[3] compared the sensitivity of a novolac negative resist to 20 keV electrons and 1.5 MeV H, He, and O ions. The resist achieves half of its maximum thickness with very much lower doses of ions. This is partly due to the fact that ions lose more energy to electron excitation and ionization per path length than do electrons, and partly due to the nonlinear affinity of immediately adjacent sites in two novolac chains to excitations that form an insoluble polymer. For the case of PMMA, K. Gamo[4] points out that the threshold dose for most ions is smaller by two orders of magnitude than the dose required by electron beam exposure. The chemical reaction of the incident beam with the resist is also a factor. Noble gas ions, being very chemically stable, would tend to evaporate from the resist. P. A. Miller and colleagues[5] measured voltage shifts in capacitors due to radiation damage from ions, electrons, and x-rays with relevant energies. The largest shifts occurred after irradiation by x-rays, indicating that x-rays typically displace more electrons in the material than do electron or ion beams. Additionally, the range of the x-rays was not affected as much by the material as that of electrons or ions. We, therefore, restricted our comparison to ions and electrons.

We now consider the optimal resolution capabilities of ions and electrons. The factors that determine resolution are the lateral and radial energy deposition, depth of penetration, straggle, and recoil electrons (the proximity effect[6]). To etch 50 Å or smaller structures in PMMA, the energy deposition must be confined to as small a region as possible. The straggle and depth of penetration must also be confined. Since scattering of ions or electrons into matter is a random process, the best control is afforded by using:

1. As few particles as possible, and
2. Particles whose depth of penetration and straggle are a function of something controllable such as the kinetic energy.

To test the limits of electron beam resolution, Chen and Ahmed[7] used a high voltage (100 keV), high resolution electron beam lithography machine to expose a 650 Å deep layer of PMMA to an electron beam approximately 5 nm in diameter and having 80 keV of energy. After exposure, a scanning electron microscope with a resolution of 7 Å was used to examine the samples. The mean line width was 61 Å, with a standard deviation of 15 Å. The resist pattern was transferred to a silicon substrate using reactive ion etching with PMMA as the mask. The etched lines in the silicon substrate were 50 to 70 Å wide and clearly defined (Reference 7, Figure 2). The uncertain quantities involved are the electron beam width, which may have been as small as 3 nm, and the exact number of electrons.

W. L. Brown and colleagues[8] asserted that the resolution of a point-source heavy ion beam is intrinsically higher than that of a point-source electron beam due to the near elimination of the proximity effect.[6] Ions scatter much less and, for ion energies less than 10 keV, produce secondary electrons of only very low energy, so their energy deposition is relatively confined. To substantiate this, Brown et al. demonstrated the lack of a proximity effect in PMMA with 60 keV lithium ion exposure.[8]

With regards to electron straggle in PMMA, Deshmukh and Khokle[9] have simulated electron trajectories on the x-y plane for a point source of 20 keV electrons entering a 8000 Å deep layer of PMMA on a 4.2×10^4 Å layer of silicon. For 25 electron trajectories the straggle is considerable (Reference 9, Figure 1) — the radial straggle is on the order of 17,000 Å. This is due to the fact that electrons are light, energetic particles, beside being negatively charged. Also of importance is the absorbed energy density, which was calculated for 5000 trajectories. The electrons lose 50% of their energy in a depth of about 450 Å and 90% by 1,400 Å (Reference 9, Figure 2).

L. Karapiperis and colleagues[10] made the following assertions about ion beam lithography:

1. Due to their heavier mass, ions scatter much less than electrons and hence ions have inherently higher resolution capabilities. Line widths of 400 Å have been demonstrated in PMMA exposed to 40 keV hydrogen ions through a fine conformable gold mask.

2. Resists such as PMMA are about two orders of magnitude more sensitive to ions than electrons.

3. Ion beams, like electron beams, lend themselves both to efficient projection printing and to focused beam direct writing in resists.

To explore these ideas, Karapiperis et al. modeled energy loss and scattering processes experienced by low energy ions in amorphous solids. They modeled fifty trajectories from a 60 keV point source of hydrogen ions penetrating a 4000 Å thick layer of PMMA on a 4000 Å thick layer of silicon. The small spread of the beam at the interface and the absence of backscattered hydrogen ions from the silicon were noted. For a depth of 80 Å, the 60 keV ion straggle is noticeably less than that of 5000 20 keV electrons.[9]

Comparison of the energy deposition of the hydrogen ions (Reference 10, Figure 4) to that of electrons (Reference 9, Figure 2) shows that the ions deposit most of their energy closer to the surface than do the electrons. As shown elsewhere,[10] this is in agreement with experiment. These comparisons indicate that hydrogen ions may be more suitable for etching in PMMA than electrons.

MODELING

We used the TRIM91 computer code[2] to study the resolution of ion beams in very small geometries. The system modeled is a point-source ion beam penetrating a two-dimensional, 50 Å thick layer of PMMA on a 50 Å thick layer of silicon. The kinetic characteristics of concern are the longitudinal range (average depth of penetration for several particles), radial straggle (average radial spread of the particles in the material), radial range, longitudinal straggle (second moment of the longitudinal range), energy absorbed per ion per Å of range, and energy absorbed per target atom as a function of target depth.

P. A. Miller and colleagues[5] point out that for the case of ions, the depth dose profile may have a sufficiently abrupt termination to allow adjustment of range so that little damage will occur to underlying critical layers. Our technique is to vary the energy of the point source until the maximum depth of penetration, without any ions or recoil atoms crossing the PMMA/silicon interface, is obtained. The number of ions is then increased to obtain a profile of the maximum amount of straggle.

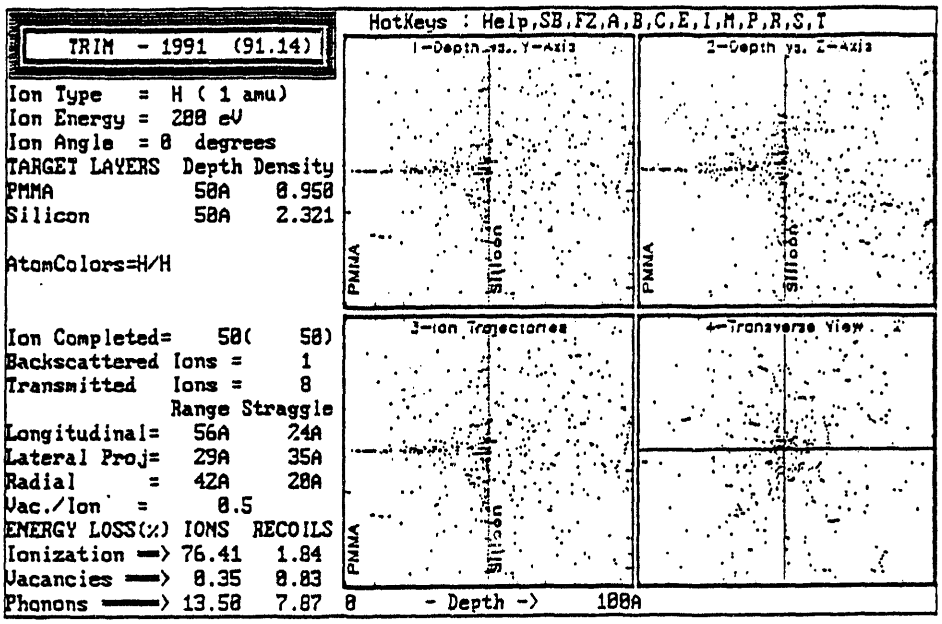
DISCUSSION

Depth profiles for 200 eV hydrogen and helium ions show 20 Å of radial straggle, see Figure 1. The PMMA/silicon interface is penetrated in both cases, and there are many backscattered atoms. We concluded that these ions are to light for this application. Radon, being radioactive, is unsuitable as well. This leaves neon, xenon, argon, krypton, and uranium to illustrate the case of a very heavy ion. Each of the noble gas ions seemed to fit the criteria at around 300 to 400 eV of energy.

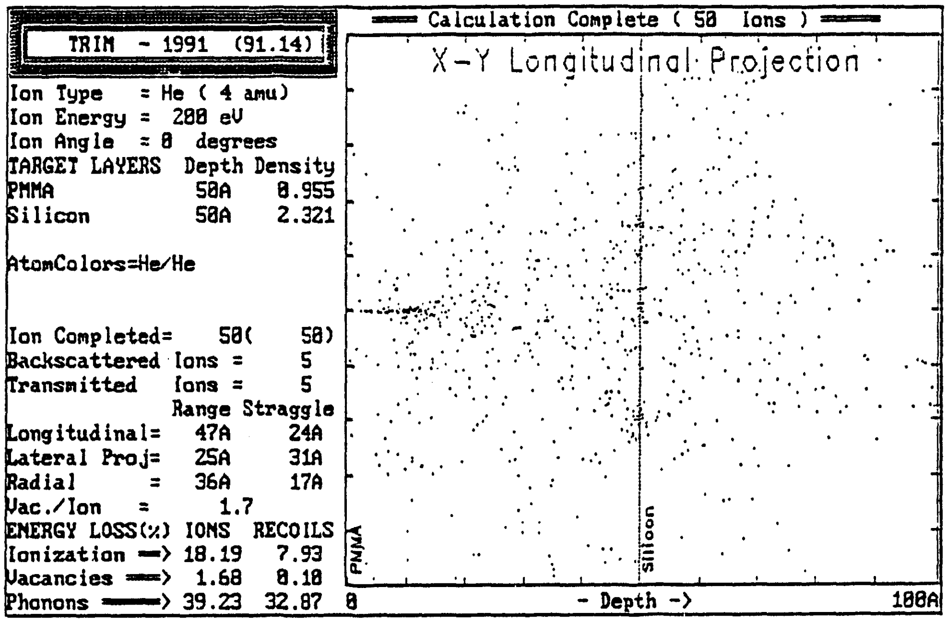
Xenon has the most compact energy deposition. For 100 ions at 400 eV, we have a radial straggle of 3 Å, a longitudinal range of 37 Å, and no backscattered or transmitted ions (Figure 2). The carbon and oxygen atoms absorb most of the energy due to their greater cross section (Figure 3); the silicon substrate absorbed no energy since ion energy is completely absorbed by a depth of 35 Å (Figure 4).

The author of the TRIM91 code indicates that the range in this case is accurate to within 40 Å and the straggle to within 10 Å. Even with these uncertainties, the energy deposition of these ions is much more confined than that of electrons. Note that a point source of 20 keV xenon ions penetrating a 1000 Å layer of PMMA (Figure 5) shows a radial straggle of 22 Å as compared to a straggle of 17,000 Å for 20 keV electrons penetrating a 8000 Å layer of PMMA (Reference 9, Figure 1).

For the case of uranium, at 300 eV the range is 44 Å with a radial straggle of 3 Å.



a. Hydrogen ions



b. Helium ions

Figure 1. Trimplot depth profile of 200 eV point source hydrogen (a) and helium (b) ions penetrating 50 Å of PMMA on 50 Å of silicon showing range, straggle, and recoil atoms.

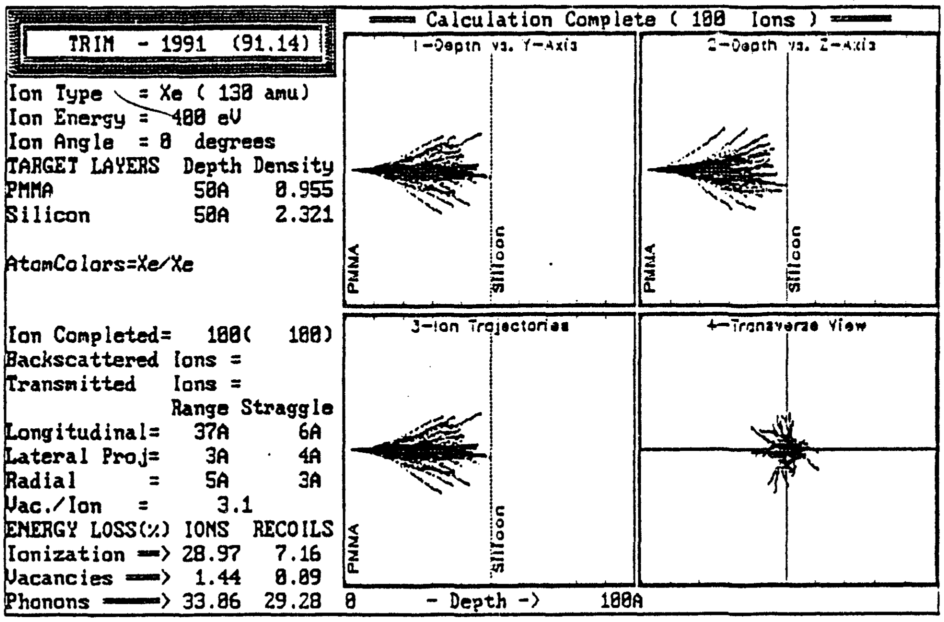
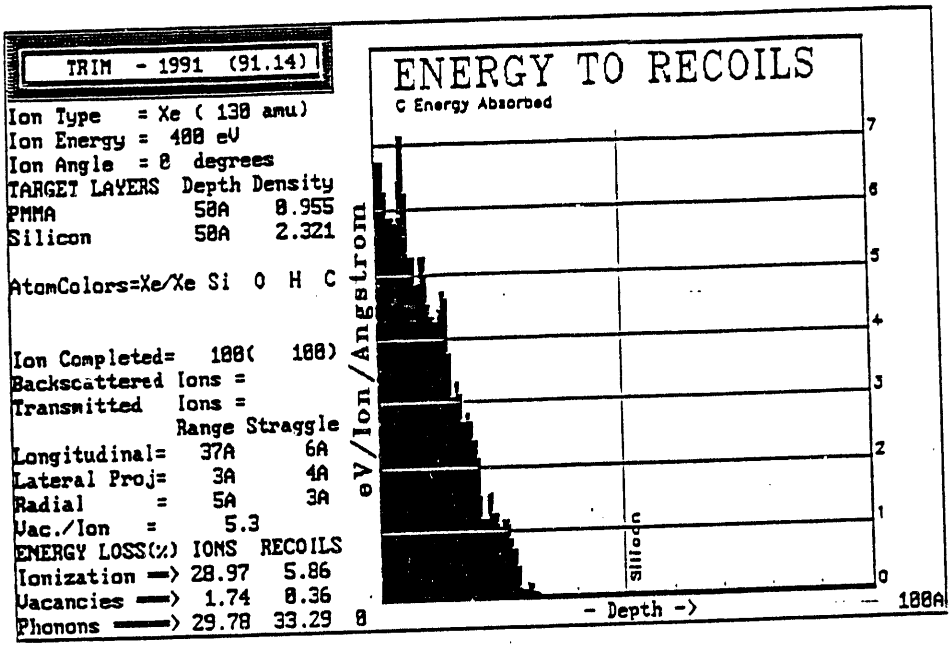


Figure 2. Trimplot profile of 400 eV point source xenon ions, penetrating the geometry modeled, showing range, straggle, and recoil atoms.

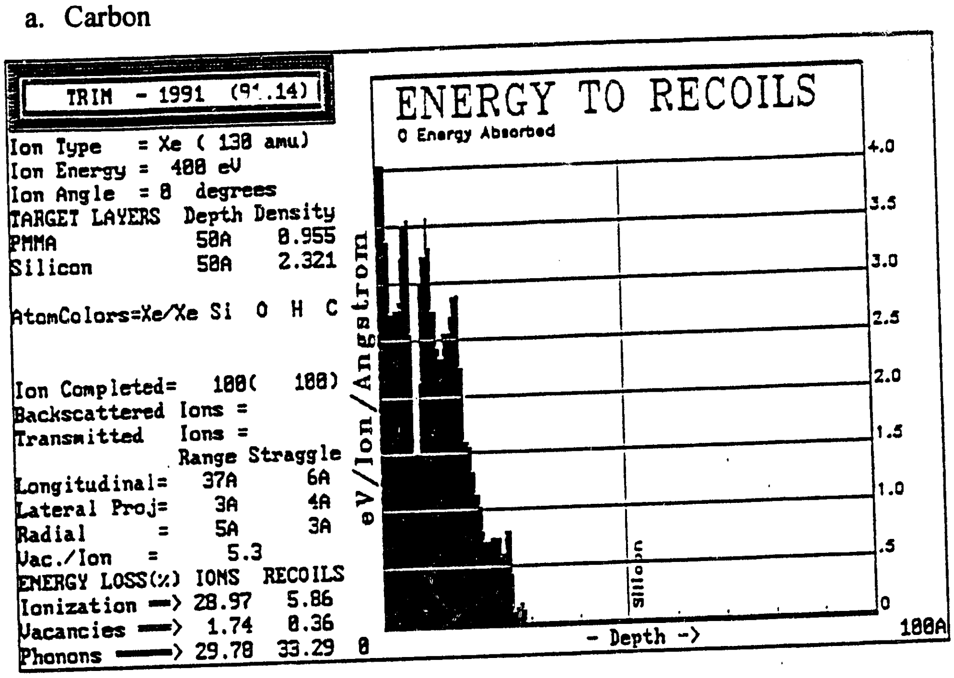
CONCLUSIONS

Considering the accuracy of the TRIM91 code, these computations suggest that xenon ions can be used to etch 50 Å or smaller features in PMMA. Using xenon ions has several advantages:

- Noble gas ions are chemically stable and tend to evaporate from the PMMA surface.
- The energy deposition density of xenon ions penetrating PMMA is greater than that of electrons, allowing fewer xenon ions to deposit the same amount of energy in the same volume.
- The number of ions required to expose a resist is two or more orders of magnitude less than that of electrons.
- Fewer ions mean fewer random events, contributing to the engineering feasibility of etching such small geometries.
- The ion energy can be tuned to a particular resist.



a. Carbon



b. Oxygen

Figure 3. Trimplot profile of energy absorbed by carbon and oxygen atoms in PMMA showing their large cross sections with respect to xenon ions.

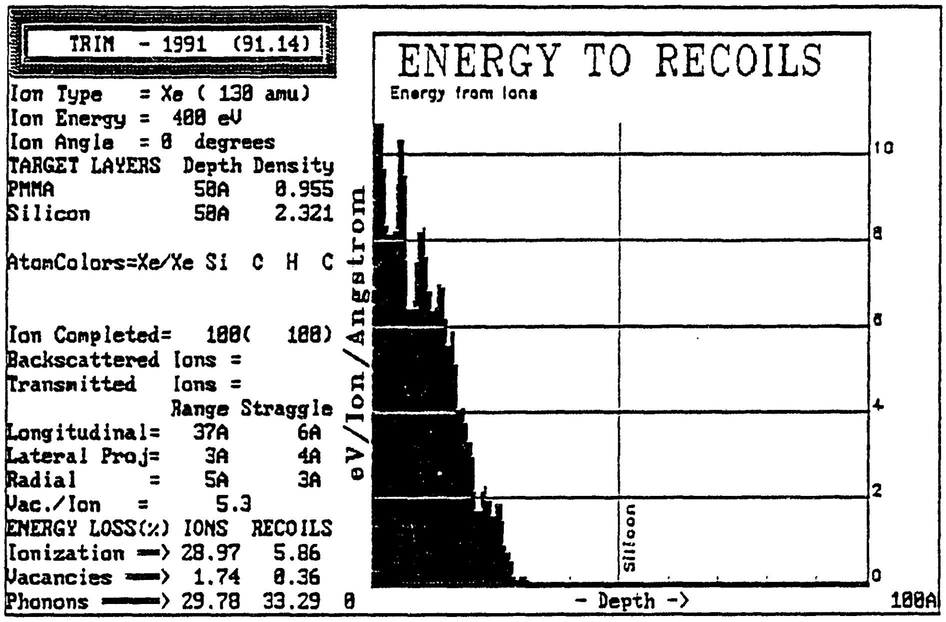


Figure 4. Trimplot profile showing that the ion energy is completely absorbed by a depth of 35 Å.

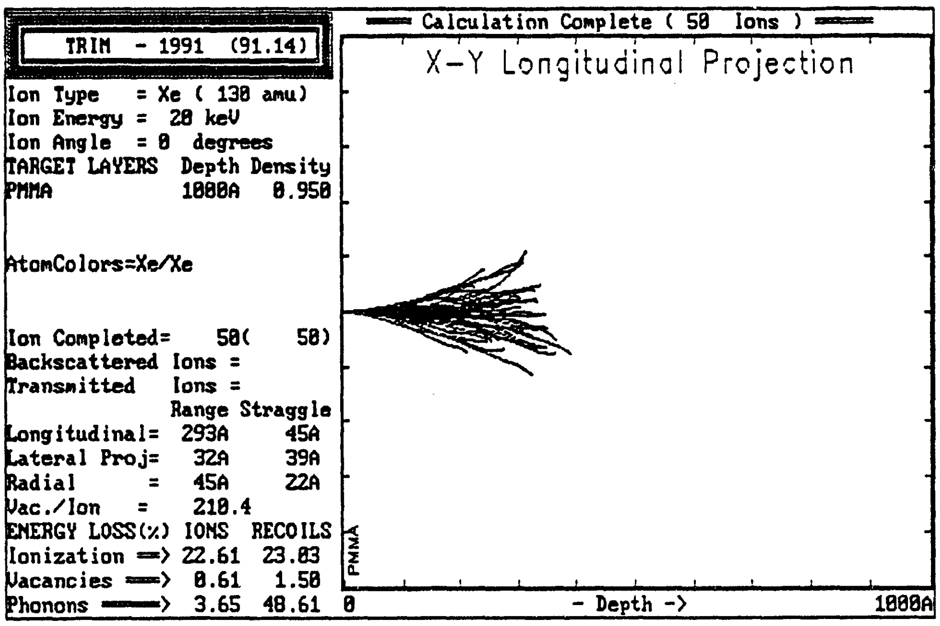


Figure 5. Trimplot depth profile of a 20 keV point source of xenon ions penetrating a 1000 Å layer of PMMA showing range and straggle.

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