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The Physics of Ion-Beam Lithography

3-1. THE FUNDAMENTAL PROCESSES IN ION LITHOGRAPHY

Ion beams are used for very diverse purposes in electronics and can be divided into three categories: 1) micromilling by removing material, 2) controlling changes in the properties of a material by doping, and 3) analyzing the structure and composition of materials. Figure 3-1 shows the physical processes that occur when an ion beam \( E < 1 \text{ MeV} \) interacts with a solid target and how they are used in electronic technology and diagnostics. The parameters of the beams used in technology and diagnostics work are shown in Table 3-1, and the energy and dose ranges of the ion beams are shown pictorially in Fig. 3-2. Thus, the physical theory presented in this chapter may be thought of as the theoretical foundation for not only ion-beam lithography, but for ion-beam technology and diagnostics as well. As can be seen, the energies of the beams used in electronics range from a few keV to 100 MeV and the doses are \( 10^8 - 10^{19} \text{ ions/cm}^2 \). A surface is machined by sputtering the material with low-energy ions. A controlled change in a material’s properties is accomplished by implanting fixed amounts of impurities in the material. Familiar examples of changing the properties of a semiconductor material are the creation of “buried layers,” isolating transistor regions in an integrated circuit, and altering the charge in the \( \text{SiO}_2 \) oxide of a \( \text{SiO}_2-\text{Si} \) structure in order to change the threshold voltage of a field-effect transistor, etc.

Interest in ion beams as tools for microlithography is comparatively recent, and the number of experiments and amount of work done in ion-beam lithography is still quite small. The physical processes that are the basis of ion-beam lithography, however, have been developed to a significant level both theoretically and experimentally. This is because wide ion beams have been used for a long time in electronics to implant impurities. A great deal of research in ion implantation has been done and the results obtained make it possible for us to evaluate the capabilities of ion-beam lithography and understand the physical processes that are the basis of this method. In turn, ion implantation has come about because of research in nuclear physics that advances our understanding of how high-energy atomic and ionic beams interact with matter. Therefore, ion-beam lithography is based on widespread physical experimentation and extensively developed.
theory. It is to be hoped that all of this will inspire the rapid development and widespread use of ion-beam microlithography in the realm of microelectronics.

As we did in discussing the physical problems encountered in electron-beam lithography, we can relate the topics of ion sources that form ion beams of submicron cross section and the physics of ion-beam interactions with matter to the physics of ion-beam lithography. Our knowledge of electron beams greatly simplifies our discussion of these topics. For example, because the theory of electron optics is totally applicable to ion beams the need to discuss ion optics is obviated. However, there are areas in which ion beams are quite different from electron beams and a detailed discussion of ion-beam physics is essential. This has mainly to do with the physics of ion-beam interactions with matter. Two factors distinguish the physics of ion beam interactions with matter from those of electron beams: the much greater mass of an ion relative to that of an electron, and the fact that an ion is essentially a multielectron system, which leads us to the fact that the energy of interaction between an ion and the atoms of a target is a more complex function of the distance between the ion and the target's atoms than can be described by Coulomb's law. The large mass of an ion produces a number of significant results, chief among which is, perhaps, the fact that a heavy ion has a great deal of momentum \( m_1 v_1 \). Transmitting this momentum to a target's atoms during a collision may dislodge the latter from the lattice sites and produce a vacancy-interstitial atom type of defect (Frenkel defects). The dislodged atom may acquire enough energy from the ion that it too may dislodge other atoms during a collision, producing a series of collisions that create a large number of Frenkel defects. At the same time, a fast electron having \( E \leq 10^5 \text{ eV} \) of energy has so little momentum that it is incapable of dislodging atoms