ION IMPLANTATION DAMAGE OF SILICON AS OBSERVED BY OPTICAL REFLECTION SPECTROSCOPY IN THE 1 TO 6 eV REGION

Stephen Kurtin, Gordon A. Shifrin, and *T. C. McGill*
Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, California 90265

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Optical reflection spectra of crystalline, sputtered, and ion implanted silicon specimens are presented. Characteristic aspects of the spectra of ion implanted specimens are related to lattice damage.

Ion implantation has been of increasing interest in recent years as a technique for the doping of crystalline semiconductors. Silicon has received particular emphasis because of its great importance in present solid-state technology. Many investigators[1,2] have observed a "milky" or hazy appearance on the surface of silicon ion implanted at room temperature. This effect appears to be general, occurring in varying degrees for all implanted species after a certain dose (specific to each ion type and ion energy) has been exceeded. It has been speculated that this "milkiness" is related to Rayleigh scattering.[3] The present paper reports the results of a preliminary investigation of the optical (1–6 eV) reflection spectra of ion implanted silicon. We find that the average dielectric properties of the ion implanted material rather than local fluctuations (Rayleigh scattering) dominate the observed spectra.

Specimens for this investigation were implanted at room temperature using an accelerating potential of 40 kV. Implantation systems having both plasma and surface ionization sources were employed. Care was taken to assure that system pressure was less than 10^{-7} Torr during all implants because surface contamination effects are observable at higher pressures. "Amorphous" silicon samples were prepared by sputtering high purity silicon onto quartz substrates at room temperature using a dc excited argon plasma discharge; pressure in the vacuum system before sputtering was about 10^{-6} Torr. Reflectance measurements were performed on a Cary Model 14 double beam spectrophotometer with a specular reflectance attachment modified to accept samples of less than 1 cm diameter. A systematic error of ±2% in absolute reflectivity applies to all the data obtained in this series of experiments.

Reflection spectra are shown in Fig. 1 for crystalline, sputtered, and several ion implanted silicon specimens. The crystalline sample was a 100-Ω-cm, *p*-type, semiconductor grade, etch-polished silicon slice obtained from the Monsanto Company. This starting material was used for all implanted specimen.

In Fig. 1(a), two reference reflectivity spectra are displayed. The solid trace was measured for unimplanted crystalline silicon. This trace is repeated as the solid curve in Figs. 1(b), 1(c). The

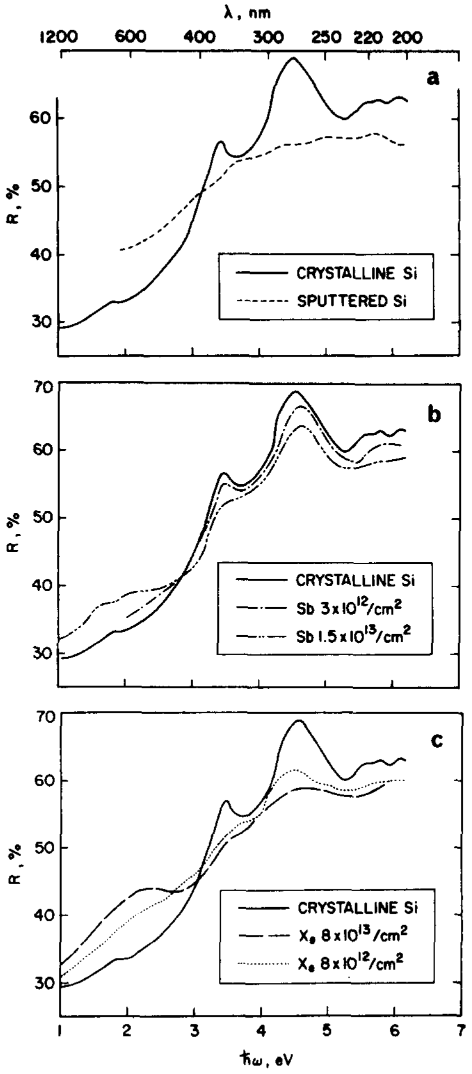

Fig. 1. Reflection spectra for crystalline, sputtered ("amorphous"), and ion implanted samples. The crystalline curve is repeated for reference in each portion of the figure: (a) sputtered silicon, (b) silicon implanted with antimony, (c) silicon implanted with xenon. All implanted were performed at an energy of 40 keV into room-temperature silicon substrates.

dashed trace of Fig. 1(a) is the average of several spectra measured for sputtered silicon. Figures 1(b), 1(c) show reflectivity spectra of silicon implanted with Sb or Xe.

In addition to the data given in Fig. 1, it was observed that:

(1) Reflection spectra of silicon samples implanted with 40-keV Ar ions are qualitatively similar to the spectra displayed in Figs. 1(b) and 1(c).

(2) Reflection spectra (3.5–6 eV) of silicon samples implanted with 40-keV Sb ions to doses of $> 10^{15}/\text{cm}^2$ were similar to, although not identical with, spectra of sputtered silicon.

(3) Sputtered silicon samples implanted with 40-keV Sb ions to doses of $> 10^{15}/\text{cm}^2$ displayed little or no change of reflection spectra in the 3.5–6 eV spectral region.

(4) Scanning electron micrography of several samples showed no evidence of surface roughness or irregularity as a result of ion implantation.

From Fig. 1(b), it is clear that the "milky" appearance of ion implanted silicon crystals arises from decreased reflectivity in the extreme blue region (3600–4200 Å) and increased reflectivity throughout the remainder of the visible. As discussed below, the observed shifts of spectral reflectivity may be interpreted in terms of changes induced by ion implantation in the average dielectric properties of silicon, in conjuntion with reflection from underlying undamaged crystalline silicon for the longer wavelengths.

Based on the theoretical calculation of Lindhard *et al.*[4] the projected range of 40-keV Sb ions in silicon is about 250 Å. If the optically effective damage associated with implanted ions is assumed to be distributed over a region of this thickness, and if the optical constants of crystalline silicon are assumed for a first-order computation, then we calculate that effects of the underlying crystalline silicon are not observable in reflection for incident photon energy greater than 3.5 eV. Lower energy portions of the reflection spectra in Figs. 1(b), 1(c) may have been influenced by an underlying crystalline layer. Since such influence greatly complicates interpretation of the observed reflection spectra, we will confine our discussion to the 3.5–6 eV region. In addition, the absence of surface irregularities, as indicated by the scanning electron microscope, implies that diffuse surface scattering does not influence the observed reflection spectra.

A salient feature of the spectra in Fig. 1 is that the optical reflectivity peaks of crystalline silicon are absent in amorphous silicon and diminish monotonically with increasing dose in all of the implanted specimens studied. These reflectivity peaks are assigned to specific interband transitions in well-ordered crystalline silicon.[5] Sputtered silicon, prepared as previously discussed, has been described as "amorphous" having short range order[6] on the scale of the basic structural tetrahedra (6 Å), but with neighboring tetrahedra rotated irregularly one from the next.[7] In view of the similarity observed between the reflectivity spectra of high dose ($>10^{15}/\text{cm}^2$) Sb implants and sputtered Si specimens we may identify the observed reflectivity spectra with a gradual conversion of an initially crystalline silicon layer to an amorphouslike state. This identification is supported by the observation that after high dose ion implantation the reflectivity spectrum of sputtered silicon evidences no changes attributable to lattice damage.

The spectra in Fig. 1 in conjunction with observation (1) indicate that the qualitative aspects of ion implantation damage in silicon, as measured by optical reflection, are general and independent of the ion species, at least for ions of mass greater than 39. In addition for a given ion dose changes in reflectivity increase with increasing mass of the incident ion. This observation is consistent with a model in which changes in the optical reflectivity spectra are correlated with lattice damage in ion implanted silicon. Changes in optical reflectivity should not be expected to scale linearly with increasing ion mass since both the extent and depth of the damage distribution are nonlinear functions of ion mass.

At present, disorder at the atomic level produced by ion implantation in silicon is not understood in detail. Electron diffraction studies[7] agree with the interpretation above that ion implantation drives the silicon lattice toward an amorphouslike structure, however the details of this transition are difficult to ascertain. Indeed, optical reflection studies may not be suitable for interpreting the spatial distribution of damage produced by ion implantation simply because optical wavelengths are many times the 50 Å size ascribed by transmission electron microscopy[3] to the central damage region surrounding each incident ion. That is, calculations indicate that under conditions appropriate to ion implantation damage in silicon, the average dielectric properties of the damaged layer determine the character of the reflectivity spectrum.[8]

We conclude that ion implantation into silicon at room temperature produces lattice damage, whose average dielectric properties are responsible for a modified optical reflection spectrum. Considering only ions of mass >39, for which sufficient data exists, the qualitative effects of ion implantation damage as observed by optical reflection spectroscopy are independent of ion species. In the high dose limit the observed reflectivity spectrum is similar to that of an "amorphous" silicon sample.

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CHANGES OF OPTICAL REFLECTIVITY (1.8 TO 2.2 eV) INDUCED BY 40-keV ANTIMONY ION BOMBARDMENT OF SILICON[*]

R. R. Hart and *O. J. Marsh*
Hughes Research Laboratories
Malibu, California 90265
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We have measured the fractional change in the optical reflectivity of silicon in the 1.8–2.2 eV photon energy band as a function of 40-keV antimony ion dose (10^{11}–10^{15} Sb/cm^2 at various implant temperatures (– 160–405°C). Approximate agreement is found between the change of reflectivity and previous measurements of lattice disorder as determined by backscattering of 1-MeV He ions.

Optical measurements of crystalline silicon, ion implanted at room temperature, show changes of reflectivity in the 1–6 eV photon energy region which are associated with the lattice damage produced during implantation.[1] To compare reflectivity changes of ion implanted Si with previous measurements of lattice disorder as determined by backscattering of 1-MeV He ions,[2-4] we have measured the fractional change in the optical reflectivity of Si in the 1.8–2.2 eV band as a function of 40-keV antimony (Sb) ion dose at various implant temperatures.

The optical reflection measurements were performed simultaneously with ion implantation of the targets which were float-zoned, etch-polished, 100-Ω-cm, *p*-type silicon. The Si samples were cut to less than 1° of the {111} face, and the surface normal was misaligned approximately 5° with respect to the ion beam to reduce channeling effects. A brightness spot meter, sensitive in the 1.8–2.2 eV band, was set at an angle of reflection of 15° from the target normal and focused to accept only light from a small area on the target surface to be implanted. Approximately uniform illumination of the target surface was provided by a tungsten lamp, which was positioned for maximum reflected light intensity. Standard glass viewports were mounted in the target chamber walls to permit transmission of the light. The output of the brightness meter was connected to one axis of an *X-Y* recorder, the other axis monitored the ion dose, as measured by a current integrator.

The Sb ion beam was magnetically mass separated and was electrically swept over the target surface to provide a uniform dose. Secondary electrons were suppressed with a biased shield to insure accurate target current measurements. The beam current density was typically 10^{-8} A/cm^2. The target chamber pressure was less than 5×10^{-7} Torr during implantation. Target temperature was maintained by either radiant heating or conductive cooling; and the temperature of the target was measured to ±5°C by a calibrated thermocouple.

The fractional change in reflectivity ($\Delta R/R_0$) as a function of ion dose (D) at various implant temperatures (–160–405°C) is shown in Fig. 1. For purposes of comparison with the room-temperature (23°C) data, the dose dependence of lattice disorder, as measured in relative units by the backscattering of 1-MeV He ions for 40-keV Sb implantations of Si,[2] is also shown (see right-hand scale). The scale for the backscattering data is arbitrarily set with respect to the scale for the optical data. The general behavior of the two curves is similar. However, $\Delta R/R_0$ is proportional to $D^{0.9}$ at low doses, as opposed to the linear increase of the backscattered results. Furthermore, $\Delta R/R_0$ saturates at approximately one-half the dose indicated by backscattering and then shows a gradual decrease at the higher doses. Preliminary measurements in other photon energy intervals show that although the slope of $\Delta R/R_0$ in this high dose region is approximately zero, it can be either positive or negative.

Variation of the implant temperature from –160–177°C does not alter the slopes of the reflectivity curves in the low dose region but does somewhat alter the value of $\Delta R/R_0$ at a given dose and also

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