INTRODUCTION

The investigation of defects in silicon by modulated optical reflectance measurements has proven to be a powerful and easy-to-use method of nondestructive materials characterization. This technique has been used to monitor ion implant dose [1] and measure polishing damage [2] in silicon wafers, and to map O₂ swirl precipitates in Czochralski-grown silicon [3]. Laser-induced modulated reflectance offers advantages over some related thermal-wave techniques: it is contactless, and because it can be performed at modulation frequencies of several MHz, it offers micron-scale resolution. Its noncontact and nondestructive nature makes this technique attractive for production-line use in the semiconductor industry.

In this paper we report the results of an investigation of the influence of specific defects in silicon on the modulated reflectance signal, and how modulated reflectance can be used to produce images of these defects. The objects of our study were arsenic- and boron-implanted silicon wafers, and 5% plastically deformed bulk silicon. Plastic deformation was chosen because it introduces a high density of dislocations throughout the silicon, and has been studied extensively via transmission electron microscopy (TEM) [4] and electron paramagnetic resonance (EPR) [5]. Ion implantation offers an means of introducing specific defects into the near-surface region of silicon wafers. Such defects are now very well understood [6]. To summarize, there are at least three types of defects which can form in implanted and annealed silicon: those formed as point defects coalesce into dislocation loops in the absence of amorphous layer formation (type-I) or in amorphized material below the amorphous-crystalline interface (type-II), and those resulting from dynamic annealing effects in wafers insufficiently cooled during implantation (type-III).

Modulated reflectance measurements and images were taken using the Therma-Probe™ [7] system, in which an intensity-modulated laser beam is used to create the thermal and plasma waves which are detected by modulated changes in optical reflectance. The apparatus has been described in detail in the literature [8]. The 488 nm beam of a 35mW Ar laser is intensity modulated from 1 to 10 MHz by an acousto-optical modulator and focused on
the sample. This beam becomes the "pump" beam and creates the thermal and plasma waves which diffuse through the sample. The periodic variation in optical reflectivity (delta-R/R) is measured by a 633 nm HeNe "probe" beam, operating at about 5 mW and focused colinearly with the Ar beam to a 1 micron spot on the surface of the sample. Most modulated reflectance signals measured in this study range from delta-R/R = 2x10^-5 to 10^-2, which is well within the sensitivity limits of the Therma-Probe. (For the remainder of this paper, delta-R/R measurements will be expressed in units of 10^-6, referred to here as "TW" or "thermal wave" units.) Imaging is accomplished by mounting the specimen on an x-y stage, and moving the stage back and forth in a raster fashion. The beam is scanned continuously, and the TW signal is sampled every 0.4 micron; the signals are stored digitally in the Therma-Probe. An image of 50 x 50 microns, then, consists of about (125)^2, or 16,000 pixels. Bright regions in the image normally correspond to areas of high TW signal, and dark regions to areas of low signal. Steady state "DC" reflectivity images can also be generated in this way. Such images are very sensitive to imperfections and debris on the sample surface (scratches, etc.), and are useful for comparison with TW images.

The samples were then examined in a Philips 301 transmission electron microscope, which allowed precise defect identification used for correlation with the TW images. Because the resolution of the modulated reflectance technique is limited to about 1 micron (the size of the pump and probe beams), low-magnification TEM images were used to identify the spatial arrangement of the defects. 2-beam bright-field images allowed Burgers vector determination of defects in the implanted wafers.

**EXPERIMENTAL**

Silicon wafers of <001> orientation were implanted with arsenic and boron at 100 KeV with doses of 3x10^14, 1x10^15, 3x10^15, and 1x10^16 ions/cm². The temperature of the wafers during implantation was not known [9]. After implantation the wafers were measured on the Therma-Probe, and then annealed at 1000°C for 30 minutes in N₂. They were measured and annealed twice more in succession, for a total anneal time of 90 minutes. After the final anneal they were measured and imaged in the Therma-Probe. Both plan-view and cross-section TEM samples were prepared from the implanted wafers, to provide information about both the spatial arrangement and depth of the defects. TEM specimens were prepared by standard mechanical lapping, polishing, and ion milling techniques. To produce plastically deformed silicon, a 4x4x20mm³ piece was cut from a silicon ingot (ca. 10¹² cm⁻³ B doped), heated to 650°C, and strained 5% in compression along a <213> axis. The dislocation density was thereafter near 10⁹ cm⁻². A 1mm thick piece was then cut along a <213> face, lapped, polished, and then chemically etched to remove polishing damage. The sample was then measured and imaged on the Therma-Probe. TEM specimens of the plastically deformed silicon were prepared by slicing a 1 mm thick disk from the bulk material along a <213> face, lapping, polishing, and milling from both sides.

Almost all TEM micrographs were bright field images taken along the <001> zone axis, under two-beam diffraction conditions using the <220> reflection for imaging. As described above, low magnification TEM images were required to match the magnification of the TW images (about 3000x). TEM magnification was limited to at least 7500X, because of the variation in thickness in the TEM samples.

**IMAGES**

**Implanted Wafers**

Modulated reflectance images and TEM micrographs of the arsenic- and boron-implanted wafers are shown in figures 1, 2, and 3. No dislocation
Figure 1: Modulated reflectance images and line scans.

a) $3 \times 10^{14} \text{ cm}^{-2}$ arsenic  
b) $1 \times 10^{15} \text{ cm}^{-2}$ arsenic  
c) $3 \times 10^{15} \text{ cm}^{-2}$ arsenic  
d) $1 \times 10^{16} \text{ cm}^{-2}$ arsenic  
e) $3 \times 10^{15} \text{ cm}^{-2}$ boron  
f) $1 \times 10^{15} \text{ cm}^{-2}$ boron  
g) $3 \times 10^{15} \text{ cm}^{-2}$ boron  
h) $1 \times 10^{16} \text{ cm}^{-2}$ boron
Figure 2. TEM images--Arsenic-implanted wafers
Figure 3. TEM images—Boron-implanted wafers
loops or other defects were visible in the TEM in either the 3x10^{14} or 1x10^{15} cm^{-2} As-implanted wafers. Modulated reflectance images also show no features in these two wafers. (The 40 micron line scans shown below the images indicate the actual signal strength and variation for each sample. The contrast was exaggerated greatly in these two images, and represents the very slight variation in the signal from point to point shown in the line scan.)

Features are evident in the TW image of the 3x10^{15} cm^{-2} As-doped sample. As verified by the plan-view TEM image, the bright features are isolated dislocation loops or clusters of loops within the top 100 nm of the wafer surface. The loops are on the order of 50 nm in diameter. As the As implant dose is increased to 1x10^{16} cm^{-2}, we see that contrast disappears again in the TW image. As is clearly shown in the TEM images, a very dense dislocation network has formed within the top 150 nm of the wafer (fig. 2d). The weak beam dark field image (fig. 2e) shows the size of these features is on the order of 50-100 nm. We believe that no amorphous layer was formed during arsenic implantation at 3x10^{14} cm^{-2} or 1x10^{15} cm^{-2}, but that the loops in the 3x10^{15} cm^{-2} wafer are type-II defects, formed below the former amorphous-crystalline interface in this wafer. The dislocation network (type-III defects) in the 1x10^{16} cm^{-2} As sample is evidence that the wafer was not cooled during implantation.

Dislocation loops and structures (type-I defects) were found in the boron-implanted samples at all doses. The 3x10^{14} cm^{-2} implanted sample shows dislocation loops at a depth of 200-300 nm below the wafer surface (fig. 3a). We see contrast in the TW image of the same sample, indicating the presence of near-surface damage. At a dose of 1x10^{16} cm^{-2} the density of loops increases and the loops begin to interact and form networks. This is reflected in the TW image (fig. 1f); clusters and strings of defects are clearly visible in this image. These are perfect dislocation loops formed by the coalescence of interstitial atoms during thermal annealing; no amorphous layer was formed during implantation in either of these two samples. At an implant dose of 3x10^{15} cm^{-2} the dislocations have formed extended networks which extend to a depth of 500-600 nm. The network structure, still relatively sparse, is clearly visible in the TW image with 1 micron resolution. At a dose of 1x10^{16} cm^{-2}, the network has become so dense that we begin to lose contrast in the TW image. It is still apparent in the TW image, however, that defects are present in the wafer. These networks have formed via dislocation-dislocation interaction among loops during thermal annealing. Because no amorphous layer was formed during implantation in these 2 wafers, the most energetically favorable way of accommodating the high concentration of interstitial atoms is to form extended dislocation networks. (In the absence of an amorphous layer, the transformation from loop to network occurs when the dose is approximately equal to the density of atoms in a (111) monolayer of silicon: 1.4x10^{15} cm^{-2}.)

**Plastically-Deformed Silicon**

The 50x50 micron² modulated reflectance image of the plastically-deformed silicon (fig. 4a) shows three intersecting sets of parallel lines. The DC reflectance image (fig. 4b) shows that most of the lines in the TW image are subsurface features. The parallel sets of lines in the TW image are slip planes resulting from the deformation. These are various (111) planes in the silicon along which dislocations move and multiply during plastic deformation. Each individual line indicates the intersection of a (111) plane with the surface of the sample; dislocations intersect the surface along these lines. This is verified in the TEM image of this material (fig. 4c). Dislocations were seen to be arranged linearly throughout the TEM sample. The 3 micron spacing between slip bands corresponds nicely with the TW image. The high overall dislocation density accounts for the high background TW signal (shown on the line scan).
Figure 4. Plastically-deformed silicon
Modulated reflectance signals from all the implanted samples are shown in figure 5 in a log-log plot. An obvious trend is that the signal decreased with each anneal over all doses for each sample, excepting one. The TW signal immediately after implant is apparently not a strong function of dose in this range. This is due to saturation of the signal resulting from the high level of implant damage at these doses. The TW signal for the \(1 \times 10^{16}\) As doped wafer after implant is significantly less than that for lower doses; this is due to modulated interference effects from the amorphous layer [10]. Amorphous layer regrowth and Frenkel pair annihilation occurred during the first 30 minute anneal, hence the first anneal achieved the greatest decrease in TW signal. The remaining annealing periods allowed the remanent dislocation structures to grow and coarsen, which has the effect of reducing the spatially average TW signal. The final TW signals can be accurately expressed as a function of implant dose by the following empirical relationships:

Boron: \(TW = (dose)^{0.86}\)
Arsenic: \(TW = (dose)^{0.95}\).

The increase in average TW signal with dose is almost entirely due to the presence of ionized dopants rather remanent implantation damage. High concentrations of ionized dopants decrease the mobility, hence the diffusivity, of the electron-hole plasma [11], thus increasing the TW signal. This is verified by the two lowest-dose As samples, which, as we have seen, contain no remanent defects. The variations in TW signal across even the most highly defective samples differ only slightly from the log-linear signal vs. dose relationship. This is strong evidence that most of the thermal wave signal in highly-implanted silicon is due to the photogenerated plasma waves and their effect on the refractive index.

This relationship between shallow dopant concentration and TW signal appears to hold only at very high doping levels. The peak As concentration in the \(3 \times 10^{14}\) cm\(^{-2}\) sample is near \(1.4 \times 10^{20}\) cm\(^{-3}\), and even this yields a TW signal of only about 40. (In "perfect" silicon, the TW signal is rarely lower than about 25.) TW measurements of phosphorus bulk-doped samples show a TW signal of 60 for bulk concentrations of \(8 \times 10^{18}\) cm\(^{-3}\).

**DISCUSSION**

The modulated reflectance images of the the As- and B-implanted wafers show contrast in cases in which the scale of the dislocation structures is on the order of or greater than 1 micron. It is not obvious, though,
whether bright areas in the TW images correspond to individual dislocation loops (see, for example, the TW image of the 3x10^{14} \text{cm}^{-2} Boron implanted wafer), or merely regions of high dislocation density. As measured from the plan-view TEM images, the approximate areal densities of dislocation loops in the samples which contain distinct loops are from 10 to 20 times as high as the densities of features (local maxima) in the TW images. This suggests that the individual dislocations themselves are not being imaged. Instead, it is likely that bright areas in the TW images correspond to clusters of dislocation loops. The TEM images show that among the boron-implanted wafers, as the dose is increased from 3x10^{14} \text{cm}^{-2} to 1x10^{15} \text{cm}^{-2}, the density of both loops and loop clusters increases. This is seen in the corresponding TW images. In the more highly implanted samples, as we have seen, the density of dislocations becomes so high that contrast decreases or disappears, and we are unable to resolve defects. We would not expect to resolve individual dislocations in the plastically deformed sample, given that the probe beam diameter is 1 micron and the dislocation density 10^9 \text{cm}^{-2}. The outstanding feature in the TW image is the linear arrangement of dislocations; this is easily resolved.

In implanted and annealed silicon wafers, the effect of remanent defects on the TW signal seems to be less than that of the ionized shallow dopants. Therefore, the magnitude of the signal is best interpreted as a measurement of the doping (in the high-dose limit), while the spatial variations of the signal can indicate the presence of near-surface defects.

CONCLUSIONS

We have demonstrated the ability of modulated reflectance measurements to detect the presence of sub-surface damage in silicon. Clear correlation with a detailed TEM study was found. The modulated reflectance signal was found to be directly related to the implant dose in implanted and annealed silicon wafers. Further work will focus on additional characterization of the modulated reflectance response in order to get information on the depth and character of particular defects.

REFERENCES

7. "Therma-Probe" is a trademark of Therma-Wave, Inc., Fremont, CA
9. The wafers were implanted by a third party, who subsequently lost all information regarding wafer temperature during implantation.
10. J. Opsal, these proceedings.