Annealing of implantation damage and redistribution of impurities in SiC using a pulsed excimer laser

S. Y. Chou,[a] Y. Chang, K. H. Weiner,[b] and T. W. Sigmon
Solid State Electronics Laboratory, Stanford University, Stanford, California 94305

J. D. Parsons[c]
Hughes Research Laboratories, Malibu, California 90265

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A 6Hα-SiC crystal sample, which has a surface amorphous layer resulting from a high-dose Ga implantation, was heated using a pulsed excimer laser at several energy fluences. At an energy fluence of 1.66 J/cm^2, the *in situ* reflectivity measurement of the surface during laser processing indicates that melting of the SiC surface has occurred. Rutherford backscattering and channeling analysis shows that the molten amorphous SiC recrystallizes using the substrate as a seed, and that the recrystallized layer has good crystal quality. Secondary-ion mass spectrometry measurements indicate that the melting, resulting from the excimer laser pulse, results in significant redistribution of the implanted Ga. This result, the first reported for SiC, suggests that the pulsed ultraviolet process can anneal the implantation damage through a melt recrystallization process, and thus could be used to dope SiC through a gas phase adsorption process.

The use of ion implantation would dramatically advance the fabrication technology for SiC devices and integrated circuits (ICs). However, to do so, one has to solve several problems associated with ion implantation in SiC, namely, (1) crystal damage and possible formation of an amorphous layer due to the implantation,[1] (2) extremely high annealing temperatures required for activating n-type dopants in SiC (> 1300 °C), with even higher temperatures required for p-type dopants,[2,3] and (3) extremely high temperatures required for redistributing the dopants.[4] At the high temperatures required, most common dielectrics used in modern device fabrication are molten and the properties of many metals or metal silicides can be changed.[5] As a result of these problems, most SiC devices are presently fabricated using *in situ* doping processes during growth of the SiC crystals. In this letter we report what we believe is the first time the demonstration of annealing of heavy implantation damage and redistribution of impurities in SiC using a pulsed ultraviolet (UV) excimer laser. These results suggest that pulsed excimer laser processing (PELP) could contribute significantly to the processing technology for SiC devices and IC fabrication.

PELP, which offers many unique advantages, can be both a localized and nonequilibrium process. The process can be localized to an area as small as 1 μm^2 by using a patterned masking material such as Al and SiO$_2$, to prevent the laser beam from entering the SiC underneath. Therefore, only the unmasked areas on the SiC substrate are heated to high temperatures (up to the melting temperature) within a few nanoseconds. Since the heating time is so short, the heating is limited to regions within a few tenths of a micron (depending on the laser beam energy and pulse duration) of the surface in the unmasked area, with essentially no propagation vertically or laterally. The short heating times (30–100 ns) can also result in nonequilibrium processes, which could lead to the formation of nonequilibrium phase crystals. This latter feature may be used to prevent the phase transition of β-SiC to α-SiC at high temperatures.

The 6Hα-SiC crystals used in the experiment were grown by the Norton process and contain an n-type impurity background of $\sim 1 \times 10^{18}$ cm^{-3}. Gallium ions are implanted to a dose of 3×10^{15} cm^{-2} into the substrate at an energy of 200 keV. As expected, due to the high-dose heavy ion implantation, the top surface layer of the SiC becomes amorphous. The implanted region is clearly visible, since the crystal surface changes color from light green to silver-gray after the implantation. Rutherford backscattering (RBS) analysis indicates that the amorphous layer is about 0.2 μm thick, as shown by the cross-hatched region in Fig. 1. Figure 1 also shows that the RBS measurement sensitivity is sufficient to detect the implanted Ga.

The excimer laser used in the experiment is a pulsed XeCl laser, operating at a wavelength of 308 nm (3.9 eV photon energy) with a pulse of duration (full width at half maximum) of about 30 ns. The original laser beam is expanded into a homogenizer which focuses the beam down to a 4 mm by 4 mm square. The energy fluence is uniform to about $\pm 3\%$ within this square. Various beamsplitters are used to control the beam energy fluence. An additional HeNe laser beam is used to monitor the melting of the SiC substrate by *in situ* measurement of the reflectivity change. The substrate was processed in an air ambient for these experiments.

We processed two regions of the 6Gα-SiC sample with the laser beam. One region of the sample, region 1, is exposed to a single excimer laser pulse with an energy fluence of 0.42 J/cm^2. The other region of the sample, region 2, is exposed to a single pulse of the excimer laser beam with an energy fluence of 1.66 J/cm^2. The reflectivity measurements made using a HeNe laser show no melting of the SiC during the heating of region 1 of the sample. However, a large change in

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[a] Present address: Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455.

[b] Present address: Lawrence National Lab., Livermore, CA 94550.

[c] Present address: Oregon Graduate Center, 19600 Von Neumann Drive, Beaverton, OR 97006.

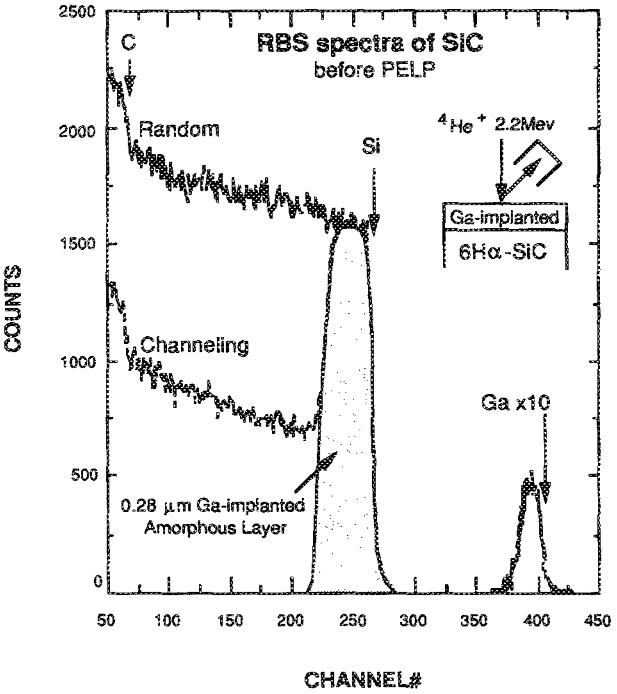

FIG. 1. Rutherford backscattering spectra taken on the SiC sample before PELP. Curve *a* is the random spectrum and curve *b* the channeling.

reflectivity was observed in the laser heating of region 2, and such a change in reflectivity is very similar to those we observe during the melting of other semiconductors, such as Si, Ge, and GaAs, suggesting that the SiC surface has melted in region 2. Visual inspection of the sample shows that the color of region 2 has changed from silver gray to a light green, very close to the color of the nonimplanted SiC crystals, while region 1 remains the gray color associated with the implant damage.

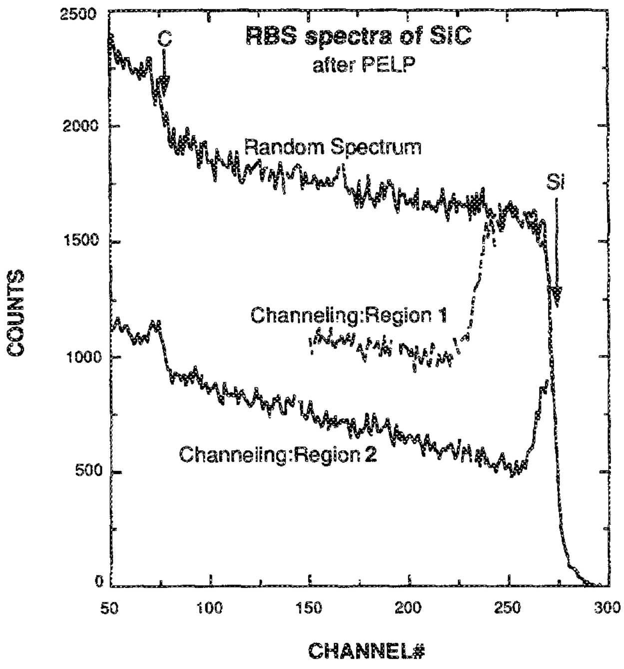

FIG. 2. Rutherford backscattering analysis of the SiC sample after PELP. Curve *a* is the random spectrum and curve *b* the channeling.

We have analyzed the two laser processed regions of this sample using 2.2 MeV ^{4}He RBS and channeling. In Fig. 2 we show the RBS spectra resulting from region 2. The channeling spectra indicate that the amorphous layer in region 2 is recrystallized by the excimer laser pulse. The small spike at the surface shown in Fig. 2 is due in part to the surface peak and possibly some residual surface oxide which forms on the cooling surface (recall the samples were processed in an air ambient). The RBS analysis shows that nothing has happended to the amorphous layer of region 1, suggesting that melting is necessary for the recrystallization of the amorphous SiC and that the recrystallization process uses the underlying bulk SiC crystal as the growth seed.

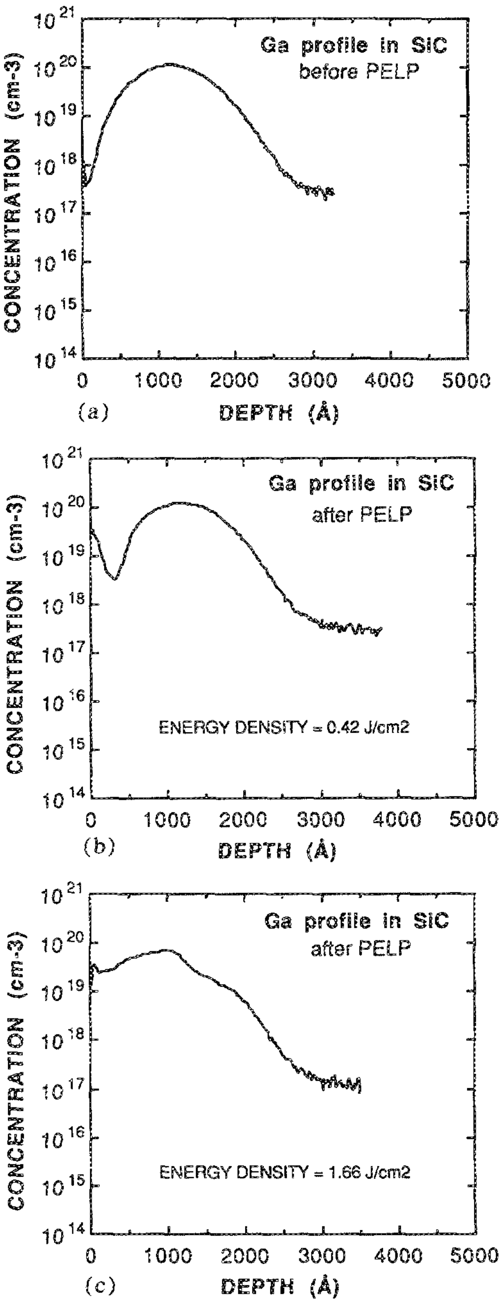

FIG. 3. Secondary-ion mass profiles of Ga in SiC (a) before PELP, (b) after PELP of an energy fluence of 0.42 J/cm^2, and (c) after PELP at an energy fluence of 1.66 J/cm^2.

We examined, using secondary-ion mass spectrometry (SIMS), the implanted Ga profile in the SiC both before and after the laser processing. The SIMS measurements are repeated at least twice on each sample to minimize any artifact effects. From Fig. 3(b) we can see that only a small redistribution of implanted Ga has occurred in region 1, when compared with the Ga profile in the unheated region. However, a significant redistribution of Ga can be seen in the SIMS data for region 2. Since the pulsed laser has a duration of about ~30 ns, this significant redistribution of the Ga dopant can hardly be explained by Ga diffusion in solid SiC, but can be well explained by Ga diffusion in a molten SiC. From Fig. 3 we can estimate that the melting depth is about 200 nm since beyond that depth the Ga profile is essentially the same as those without laser processing. The shape in the Ga profile in this region is believed to be due to redistribution caused by velocity dependence of the segregation coefficient.

In summary, we have annealed Ga-implanted 6Hα-SiC crystal samples, which had a surface amorphous layer resulting from a 3×10^{15} cm^{-2} Ga implantation, using a pulsed XeCl excimer laser. We have observed, for the first time, that a pulsed excimer laser beam with a wavelength of 308 nm and an energy fluence of 1.66 J/cm^2 can melt the surface layer of SiC, and that the molten amorphous SiC regrows epitaxially on the underlying substrate. Furthermore, we have observed for the first time that the melting of SiC with an excimer laser pulse can cause significant redistribution of implanted Ga.

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