Magnetic Properties of Fe- and Mn-Implanted SiC

N. Theodoropoulou, a A. F. Hebard, a S. N. G. Chu, b, * M. E. Overberg, c, ** C. R. Abernathy, c, * S. J. Pearton, c, * R. G. Wilson, d and J. M. Zavada a

aDepartment of Physics, bDepartment of Materials Science and Engineering, University of Florida, Gainesville, Florida 32611, USA
cBell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA
dConsultant, Stevenson Ranch, California 95131, USA

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There is currently a great deal of interest in the synthesis and characterization of dilute magnetic semiconductors, in which spin-polarized transport could be exploited in a range of devices. Characterization of dilute magnetic semiconductors, in which spin-theoretical fronts. A major drawback of these materials systems is still the subject of intense effort on both the experimental and theoretical fronts. A recent theoretical prediction of much larger values for the Curie temperature, T C. The highest reported values for T C are ~35 K for (In, Mn)As and 110 K for (Ga, Mn)As.

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In this paper, we report on the magnetic properties of p-SiC implanted with high doses of either Mn or Fe. We find that both (Si, Mn)C and (Si, Fe)C show apparent ferromagnetic behavior up to approximately 250 K with implant concentrations of ~5 atom %. This Curie temperature is below room temperature, but might be increased by having higher hole densities in the SiC if carrier-mediated processes are the cause of the ferromagnetism.

Bulk 6H-SiC wafers (Al doped) with a room temperature hole concentration of ~10 17 cm -3 were implanted into the Si-face with either 250 keV Mn + or Fe + at doses of 3-5 × 10 16 cm -2 . The samples were held at ~350°C during the implant step to avoid amorphization. The implant conditions were designed to produce average Mn or Fe concentrations of 3 or 5 atom % over a depth of ~200 Å into the SiC. The samples were subsequently annealed at 700°C under flowing N 2 with the implanted side face down on a Si wafer. The structural properties were examined by transmission electron microscopy (TEM) and selected area diffraction pattern (SADP) analysis. The magnetic properties were measured on a Quantum Design SQUID magnetometer.

Figure 1 shows a cross-sectional view of the SiC implanted with 5 atom % Fe after annealing at 700°C. There is relatively light

* Electrochemical Society Fellow.
** Electrochemical Society Student Member.
E-mail: spear@mail.mse.ufl.edu

Figure 1. Cross-sectional TEM micrographs of SiC implanted with 5 atom % Fe and annealed at 700°C.
residual damage in the form of dislocation loops to a depth of \(0.19\) \(\mu\)m from the surface, followed by a 260 \(\AA\) thick heavily defective region at the end-of-range of the Fe\(^+\) ions. The results were similar for the Mn-implanted SiC, as expected due to the near-identical masses of \(^{56}\)Fe and \(^{55}\)Mn.

Figure 2 shows the magnetization curve at 10 K for the SiC implanted with 5 atom % Fe. A strong diamagnetic contribution, which was measured at higher fields, was subtracted. The absence of a true saturation in the magnetization is a fairly common feature of dilute magnetic semiconductors such as In\(_{0.95}\)Mn\(_{0.05}\)As and Ga\(_{0.95}\)Mn\(_{0.05}\)As and its physical origin is not yet clear.\(^{10,11}\) The material implanted with 3 atom % Fe did not show any signature of ferromagnetism. Since the Curie temperature is predicted to be a strong function of both the hole concentration and magnetic ion concentration in wide bandgap dilute magnetic semiconductors,\(^{12}\) the lower dose samples may be below the threshold for inducing ferromagnetism. A similar effect was observed in Mn-implanted GaN, where doses below 3 atom % did not produce ferromagnetism.\(^{16}\)

Figure 3 shows the temperature dependence of the difference between the field-cooled (FC) and zero field-cooled (ZFC) magnetization for the 5 atom % Fe sample. The inset of the figure shows the raw data. The subtraction of ZFC from FC data advantageously eliminates para- and diamagnetic contributions and simultaneously indicates the presence of hysteresis if the difference is nonzero. Although ferromagnetism is the usual explanation for hysteresis, spin-glass effects or superparamagnetism can also be the cause. All of these effects however are magnetic phenomena involving the ordering of spins, and it is in this sense that we refer to the hysteresis measured by the FC-ZFC data in Fig. 3 as “ferromagnetic.” It is clear that a remnant of a ferromagnetic contribution is present even at room temperature. The origin of ferromagnetic behavior in implanted SiC is still not clear; we did not observe secondary phases involving precipitation of Fe or formation of FeC\(_x\) or FeSi\(_x\) compounds. Both plan-view and cross-sectional samples were examined.

Figure 2. Magnetization curve at 10 K of SiC implanted with 5 atom % Fe and annealed at 700°C. The coercive field is about 50 G. For comparison, the saturation magnetization for Fe is 220 emu/g.

Figure 3. Temperature dependence of the difference between field-cooled and zero field-cooled magnetization for the 5 atom % Fe sample. The inset shows the raw data.

Figure 4. Temperature dependence of the difference between FC and ZFC magnetization for the 5% Mn sample.

Figure 5. Magnetization curve at 10 K of SiC implanted with 5 atom % Mn and annealed at 700°C.
and no evidence of second phase formation was found. While it might be expected that the solid solubility of Fe would be relatively low in SiC ($<10^{17}$ cm$^{-3}$), ion implantation is a nonequilibrium process and as long as the postimplant anneal temperature is kept low, then much higher concentrations of Fe can be incorporated. Moreover, the implanted region was relatively resistive; the capacitance-voltage measurements showed depletion beyond the Fe range after the implantation and the annealing process, and the hole concentration was $<10^{15}$ cm$^{-3}$ in that region. Whether the remaining hole density is sufficient to induce carrier-mediated ferromagnetism in the SiC needs additional work to answer, involving substrates of different conductivity level and type. There is theory proposed in the literature that random doping effects in wide band-gap materials could be sufficient to explain the magnetism observed.

We also observed ferromagnetic contributions to the magnetization of SiC implanted with 5% Mn samples, albeit at a lower level compared to Fe as a magnetic impurity. The difference between the FC and the ZFC magnetization data is shown in Fig. 4 for the sample implanted with 5 atom % Mn and annealed at 700°C. In Fig. 5, the magnetization curve of SiC(Mn) shows that, at 10 K, there is hysteresis in the magnetization. A coercive field of 150 G was observed. This shows the usefulness of the ion implantation technique in being able to introduce a range of different impurities into the host semiconductor and being able to screen those that are the most promising for magnetic applications. The implant process is also attractive for its ability to create selective area magnetic regions that might be employed as spin-injection contacts in device structures.

In summary, high doses of Fe$^+$ or Mn$^+$ have been implanted into p-SiC. Both the Mn- and Fe-implanted material show a ferromagnetic contribution below $\sim 250$ K for Fe and Mn concentrations of $\sim 5$ atom %. Future work needs to focus on trying to increase the Curie temperature in the SiC doped with Fe or Mn and to understand the microscopic origin of the ferromagnetism.

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