DOI: 10.1017/S1431927605507487
Microsc Microanal 11(Suppl 2), 2005

Microstructure of As-implanted and Annealed Si:Mn Dilute Magnetic Semiconductors

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Semiconductor devices which exploit the spin of the electron (spintronics) offer enormous potential for high-speed and low-power applications [1]. For this purpose, diluted magnetic semiconductors (DMS), i.e., semiconducting materials exhibiting ferromagnetic behavior, have been fabricated by doping a semiconductor crystal with an additional transition metal impurity such as Mn [2-5]. Recently researchers at CNSE have reported [6] above room temperature ferromagnetic behavior for n- and p-type silicon wafers (Fig. 1) implanted with 300-keV Mn + ions at 350°C at fluences of 1-10 $\times 10^{15}$ cm $^{-2}$, reaching peak concentrations of 0.1–0.8 at.%.

SIMS depth profiling of the as-implanted samples showed a typical implantation distribution of Mn ions in the silicon lattice, with a peak depth of ~250 nm (open symbols in Fig. 2). Post-implant annealing was used to reduce the damage from the ion implantation process, which also resulted in a periodic redistribution of Mn (filled symbols in Fig.2). Although the number, height and distribution of the post-annealing peaks depended on the initial implantation fluence, the underlying mechanism driving this redistribution remained unclear. Thus a TEM study was undertaken to investigate the microstructure of the as-deposited and annealed films. Diffraction contrast TEM (Fig. 3) of an annealed film reveals a rich defect microstructure in the implantation damage zone consisting of a dense band of dislocation and stacking faults. There is, in addition, an abundance of nanometer size precipitates distributed throughout the film, with peak nanoparticle densities corresponding approximately to the observed peaks in the SIMS spectra. Selected area diffraction (inset, Fig. 3) suggests these precipitates are a Mn-rich phase that, although not thermodynamically favored in the Si-Mn system, may have a lower nucleation barrier than the equilibrium phase. These precipitates are fully crystalline, as can be seen from the high-resolution image in Figure 4. The shape of the fine structure of the Mn 3,2 edge of the EELS spectra will be discussed as related to the identity of these nanoparticles.

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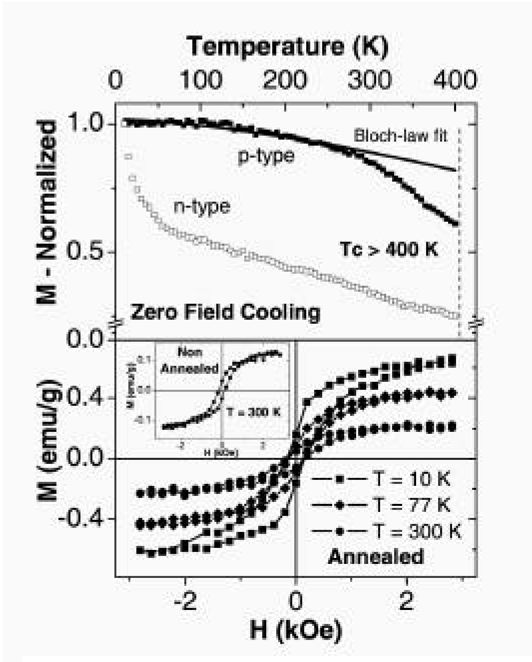

Figure 1. (top) Temperature dependence of the normalized remnant magnetization for Mn-implanted Si both p-type (solid markers) and n-type (open markers). (bottom)Ferromagnetic hysteresis loops at 10, 77, and 300 K from Mn-implanted Si after rapid thermal annealing. The inset shows a ferromagnetic hysteresis loop at 300 K before annealing.

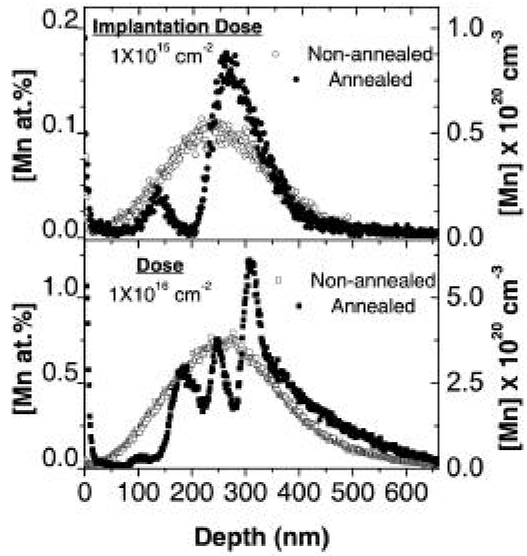

Figure 2. SIMS depth profiles of as-implanted and annealed samples with two different initial fluences of Mn. In both cases, the Mn redistributes into a series of distinct populations.

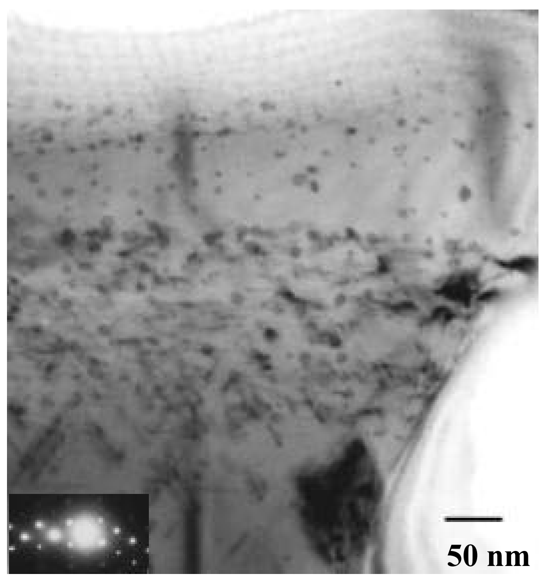

Figure 3. Off-axis bright field TEM image of the 0.6% Mn-implanted sample, after annealing. The implant damage is still evident as a band of dislocations and stacking faults, along with a plentiful population of Mn-rich precipitates.

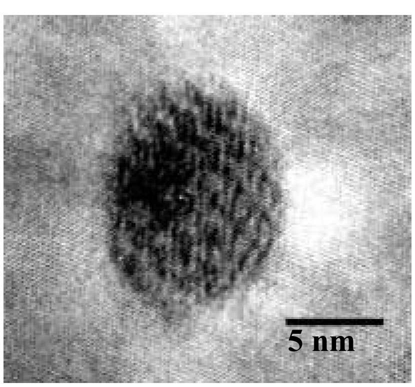

Figure 4. High resolution TEM image of a Mn-rich crystalline precipitate. Typical diameters ranged from 5-15nm.

https://doi.org/10.1017/S1431927605507487 Published online by Cambridge University Press