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EXAFS AND XMCD INVESTIGATIONS ON THE Mn$^+$ IMPLANTED SILICON CRYSTALS

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Semiconductor devices using the spin of electrons have attracted much attention because of their expected applications in spintronics. The key to the spintronic's success is availability of suitable materials for device manufacturing. Diluted magnetic semiconductors (DMS) have been shown to be the best materials for such purpose. Usually, the Mn-doped III-V and II-VI compounds forming DMS have been in the center of attention. However, there is another interesting class of materials, namely the Si-based DMS. Among them, silicon implanted with Mn ions seems to be a promising combination. The implantation of Mn$^+$ ions into a silicon matrix is a good way of exceeding the solubility limit of Mn in Si. Moreover, it has been already shown that the Mn-implanted Si samples can be ferromagnetic with a Curie temperature (T_C) higher than 400 K [1]. On the other hand, the ferromagnetic properties were also reported for silicon samples implanted with non-magnetic ions, *e.g.* Si. Therefore, it is important to find out the origin of the magnetic properties in this kind of materials.

A direct way to check whether the magnetism is related with the Mn atom cores is to perform core level X-ray magnetic circular dichroism (XMCD) studies, which allow to detect the local magnetic moments for the specific element what is not possible in the superconducting quantum interference device (SQUID) measurements.

The samples were prepared by Mn$^+$ implantation into silicon wafers grown by Czochralski method (Cz-Si) or by floating zone method (Fz-Si). The energy of Mn$^+$ ions was of 160 keV and a dose of 1×10^{16} cm^{-2}. The implanted samples were subsequently annealed at temperatures from 275°C to 1000°C under pressures of 1 bar or 11 kbar. The SQUID measurements showed that samples after low temperature annealing (up to 450°C) exhibited ferromagnetic properties [2].

The Extended X-Ray Absorption Fine Structure (EXAFS) measurements, as an element specific method, provides information about the local atomic structure around the chosen element, Mn in this case, and enables to monitor the results of the annealing.

The EXAFS measurements at the Mn K-edge were carried out at Hasylab (A1 and E4 stations) using a seven element silicon fluorescence detector. The samples were cooled to liquid nitrogen temperature in order to minimize thermal disorder.

The XMCD spectra at the Mn $L_{3,2}$-edges were measured at MAX-lab (beamline I-1011). The measurements were carried out at room (RT ~300 K) and liquid nitrogen (LN ~100 K) temperatures under an applied magnetic field of 0.1 T, along the x-ray path. The total electron yield detection mode was used. Two angles of incidence were chosen as follows: grazing (20° to the sample surface) and normal (90° to the surface).

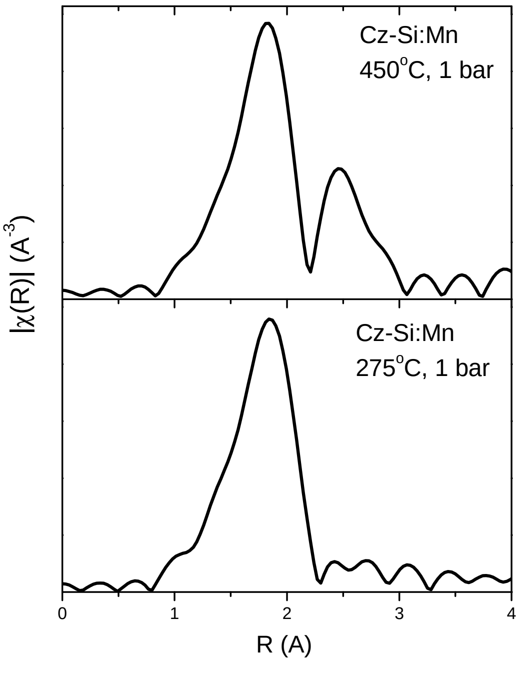

Figure 1. Magnitude of the Fourier Transform of the EXAFS spectra of the Cz-Si:Mn samples annealed at 275°C and 450°C (1 bar).

The local structure around the Mn atoms, as found out by the EXAFS analysis at the K-edge of Mn, exhibits the differences between the samples prepared by both methods and annealed at 275°C. In the case of Fz-Si:Mn sample, the Mn atoms gather together forming nanoinclusions consisting of a Mn_xSi_y compound [3]. In the case of Cz-Si:Mn annealed at low temperature, the EXAFS analysis showed only silicon neighbors. [4]

Figure 1 presents the Fourier Transformed EXAFS oscillations of the Cz-Si:Mn samples annealed at 275°C and 450°C (1 bar). It is easily seen, that the local crystallographic environment of the Mn atoms, depends on the heat treatment. For the sample annealed at 275°C, only the nearest neighbor shell is visible. In the case of the Cz-Si:Mn sample annealed at 450ºC, a second neighbor shell appears, a fact which suggests that the crystallization of the inclusions already starts. For the Fz-Si:Mn sample, only the first shell can be distinguished for both annealing temperatures (Fig. 2). It seems that the temperature of the inclusions formation process depends on the method of the sample growth.

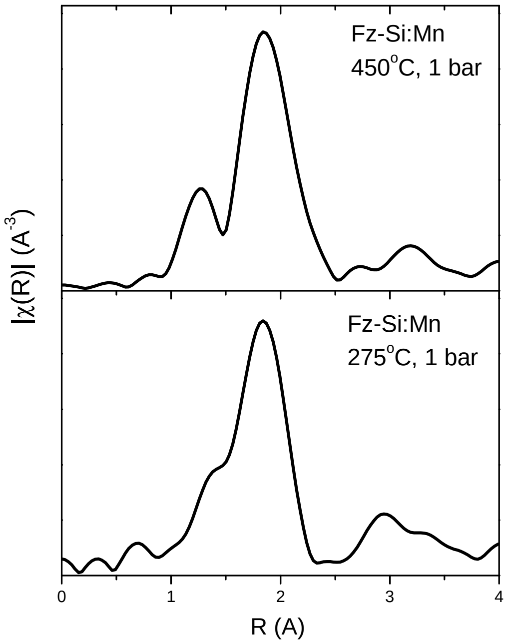

Figure 2. Magnitude of the Fourier Transform of the EXAFS spectra of the Fz-Si:Mn samples annealed at 275°C and 450°C (1 bar).

The XMCD measurements are presented in Fig. 3. A dichroic signal is not found for the considered Si:Mn samples. It seems that the Mn atom cores are not the main source of ferromagnetism in these samples. It is possible that ferromagnetism in these samples is mainly induced by the defects in the matrix caused by the ion implantation. This conclusion is supported by the fact that the high temperature treatment leading to recrystallization of the matrix seems to eliminate the ferromagnetic response in the investigated samples.

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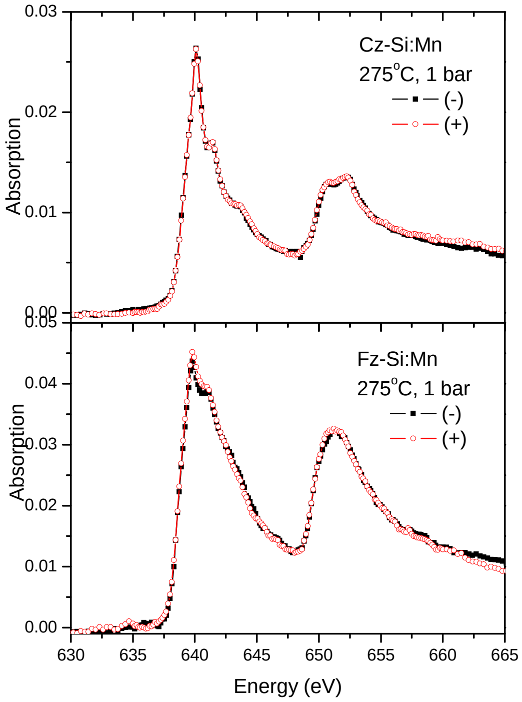

Figure 3. XANES spectra of Mn $L_{3,2}$ edges for Cz-Si:Mn and Fz-Si:Mn samples annealed at 275°C. Measurements were performed at normal incidence at RT by inverting the magnetic field direction.

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