Magnetic and structural properties of ZnO implanted by Co, Kr, Ar ions

J. B. Gosk[1], Z. Werner[2], G. Kowalski[3], M. Tokarczyk[3], R. Puźniak[4], and M. Barlak [2]

[1]*Faculty of Physics, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland*
[2]*Nuclear Centre for Research, Sołtana 7, 05-400 Otwock, Poland*
[3]*Institute of Experimental Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[3]*Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland*

ZnO suitably doped with manganese is considered as a potential and promising candidate for spintronics applications. Unfortunately, equilibrium methods of growing ZnO doped with transition metals (TM) usually lead to undesired ferromagnetic (FM) precipitations. Recently, ion implantation is frequently studied to demonstrate its suitability to obtain expected/appropriate DMS. However, in the literature there is still lack of agreement on the origin of magnetic response in implanted ZnO. Authors frequently concluded that implantation defects rather than the TM impurity give rise to the observed magnetization. It was suggested that FM or paramagnetic (PM) phases observed in ZnO is either entirely defect related or due to an interaction between defects and implantation-introduced impurity, also those without magnetic moments. Previously [1] it was shown that ZnO implanted by Co revealed PM phase while electron and proton irradiation defects are magnetically inactive.

Here, we report on magnetic properties of ZnO implanted with Co, Ar (a noble gas lighter than Co), and Kr (a noble gas heavier than Co). For the initial Co implantation (110 keV, $2{\cdot}10^{16}$ cm^{-2} fluence), the appropriate/relevant energies and doses were 70 keV, $3.14{\cdot}10^{16}$ cm^{-2} and 160 keV, $1.37{\cdot}10^{16}$ cm^{-2} for Ar and Kr, respectively. For a comparison purposes, double fluencies ($4{\cdot}10^{16}$ cm^{-2}, $6.3{\cdot}10^{16}$ cm^{-2}, and $2.75{\cdot}10^{16}$ cm^{-2}, for Co, Ar, and Kr, respectively) were also applied.

The samples in the form of two glued plates, 5×5 mm squares, were prepared from commercial Mateck ZnO single crystals of [100] orientation. For properly selected energies and doses (to have comparable implantation damages due to Co, Kr, and Ar) six samples were implanted at 500 keV implanter at HZDR, Rossendorf, Germany. Carbon coupons were implanted together with the samples to confirm the applied doses by Rutherford Back Scattering (RBS). Magnetization of each sample was measured before and after implantation as a function of magnetic field (up to 7 T) and temperature (2–400 K) using a SQUID MPMS XL magnetometer. The implanted samples were also characterized by channeled Rutherford Back Scattering (cRBS) using 1.7 MeV He ion beam and by XRD. X-ray diffractometer employing Cu $K_{\alpha 1}$ wavelength and equipped with Bragg mirror with standard X-ray optics was used. Results clearly show changes to the irradiated lattice as a function of dose and the ion type used for implantation. Crystal lattice of the samples was modified mainly by introduction Bragg planes tilts rather than interplanar spacing changes.

The magnetization measurement revealed the appearance of the PM phase in ZnO implanted by Co ions. The magnetic moment equal to about 2 μ_B per one implanted Co ion in the case of higher dose – $4{\cdot}10^{16}$ cm^{-2} and to about 1.66 μ_B in the case of lower dose – $2{\cdot}10^{16}$ cm^{-2} were observed, respectively. On the other hand, no changes in magnetization were observed in ZnO implanted by Kr and Ar ions. Thus, we couldn't find any evidence that irradiation damages caused by Kr and Ar ions, in the range of ion energies and fluencies used by us, could result in magnetic response.

[1] Z. Werner, J. Gosk, A. Twardowski, M. Barlak, C. Pochrybniak, *Nuclear Instruments and Methods in Physics Research* **B 358** (2015) 174–178