Neutron Reflectometry Investigates Mechanisms for Improving Ferromagnetic Semiconductors

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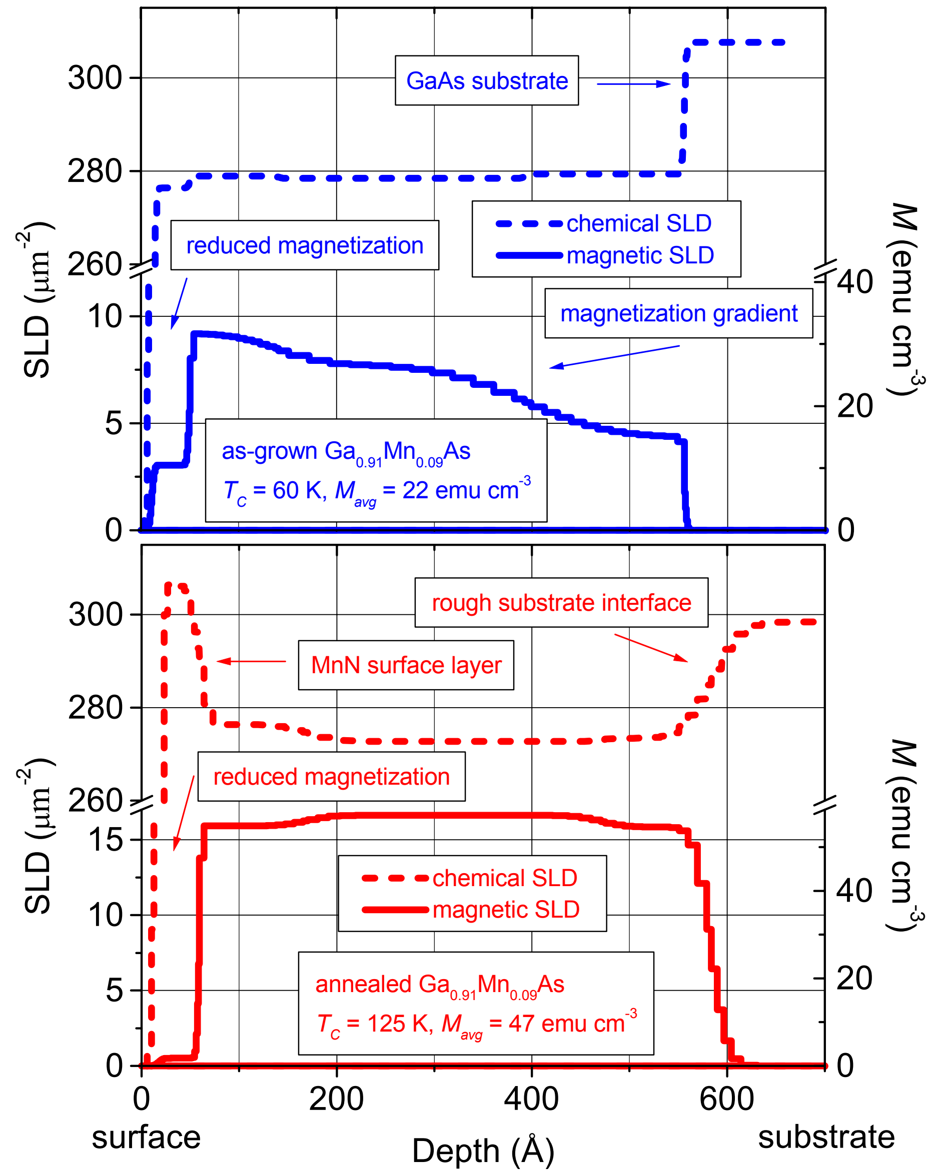
- Annealing dramatically increases the Curie temperature and magnetization of the ferromagnetic semiconductor $Ga_{1-x}Mn_xAs$ – but how?
- Answers have been provided by polarized neutron reflectometry (PNR), which by probing the scattering length density (SLD) reveals depth-dependent chemical and magnetic properties of magnetic films.
- Recent PNR measurements on $Ga_{1-x}Mn_xAs$ (x = 7 - 9 %) have
  - revealed that as-grown films frequently have pronounced magnetization gradients that "smooth out" upon annealing
  - shown that annealing tends to roughen the substrate interface
  - confirmed that annealing diffuses unwanted interstitial Mn impurities to the surface, reinforcing the ferromagnetic coupling between other Mn at Ga sites, causing the rise in Curie temperature and magnetization.



There is a great deal of interest in the development of “spintronic” devices. This technology aims to move beyond utilizing only the charge of electrons (as is the case in conventional electronics) by additionally exploiting electron spin (an intrinsic property that gives electrons north and south magnetic poles). High temperature ferromagnetic semiconductors could be very useful components of practical spintronic devices, as they can generate a *spin polarized* electric current in which most of the electron magnetic poles are aligned in a particular direction. $Ga_{1-x}Mn_xAs$ (where a small amount of magnetic Mn atoms are forced into common GaAs) is a ferromagnetic semiconductor of particular interest, as it remains ferromagnetic up to relatively high temperatures. However, while *relatively* high, the ferromagnetic transition temperature (Tc) is still well below room temperature ($Tc \approx$ -170 °F). The usefulness of $Ga_{1-x}Mn_xAs$ is likely to be largely determined by how much higher Tc can be raised. It has been known for some time that Tc, and the magnetization (M) in $Ga_{1-x}Mn_xAs$ can be increased through a heating treatment known as annealing. However, it has only been recently that researchers have gained an understanding of why annealing works in this way. We have contributed to this understanding of the annealing process by examining $Ga_{1-x}Mn_xAs$ films with polarized neutron reflectometry (PNR), a technique used to examine the depth-dependent chemical and magnetic properties of nanoscale materials. We have found that through annealing, pronounced magnetization gradients were smoothed out, and unwanted impurities were released and brought to the surface. These results supported other work suggesting that removal of impurities allows for better “communication” among the magnetic Mn atoms, causing them to align in a more uniform fashion, resulting in increased Tc and M. This study is a valuable step in determining if Tc of $Ga_{1-x}Mn_xAs$ can be pushed further towards room temperature. A portion of this work was published in *Physical Review B* (B. J. Kirby, *et al.*, Phys. Rev. B **69**, 81307 (2004)).

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Through this project, we have

- Fabricated high quality $Ga_{1-x}Mn_xAs$ films, and successfully enhanced their ferromagnetic properties via annealing
  - Controlling the magnetic properties of ferromagnetic semiconductors is important for developing devices that exploit the coupling of spin and charge (the concept of spintronics).
- Used PNR to examine the ways in which annealing works
  - Understanding the annealing process is of utmost importance for determining if *room temperature* ferromagnetic semiconductors can be developed.
- Provided a graduate student with an education in neutron scattering and magnetic semiconductors. This student is now a postdoc working in PNR at Los Alamos National Laboratory.
  - With the upcoming completion of the Spallation Neutron Source, training young scientists in neutron scattering is a national priority.