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Properties of ferromagnetic Ga$_{1-x}$Mn$_x$P thin films synthesized by ion implantation and pulsed-laser melting

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The study of other III-Mn-V ferromagnetic semiconductors in addition to Ga$_{1-x}$Mn$_x$As is crucial to elucidating the nature and details of ferromagnetism in these systems [1]. We have synthesized ferromagnetic Ga$_{1-x}$Mn$_x$P films with nominal $x \leq 0.06$ and $T_C$ up to 65 K using ion implantation and pulsed-laser melting (II-PLM). We have previously produced Ga$_{1-x}$Mn$_x$As films having $T_C$ above 130 K and displaying behavior in line with well-annealed Ga$_{1-x}$Mn$_x$As films grown by molecular beam epitaxy [2-4].

These Ga$_{1-x}$Mn$_x$P samples are insulating for $x \leq 0.06$ and $\rho_{xx}$ shows a change in activation energy near $T_C$. The anomalous Hall effect is similar to but larger than that from ferromagnetic Ga$_{1-x}$Mn$_x$As and $\rho_{xx}$ displays large negative magneto-resistance (up to ~44% at 7 T). $T_C$ and other properties scale both with Mn content and with carrier concentration. Transmission electron microscopy, X-ray diffraction, and ion-channeling demonstrate that these films are single-crystalline and epitaxial (unlike [5]) and analysis of the ion-channeling results demonstrates that no interstitial Mn is present. SQUID magnetometry reveals in-plane magnetization and anisotropy characteristics similar to Ga$_{1-x}$Mn$_x$As films. Mn L$_{2,3}$ X-ray absorption reveals a peak structure identical to that from properly annealed and etched Ga$_{1-x}$Mn$_x$As [5,7]. Magnetic circular dichroism at the Mn L$3$ edge follows the sample hysteresis loop and reaches ~30% at 5 kOe.

These measurements establish the presence of a carrier-mediated ferromagnetic phase in Ga$_{1-x}$Mn$_x$P similar to that observed in Ga$_{1-x}$Mn$_x$As. Fascinating differences arise because of the deeper (<400 meV) Mn acceptor level in GaP; far-infrared photoconductivity and resistivity reveal an excitation gap of ~25 meV and infrared absorption shows a peak near 400 meV. Based on these observations and the behavior of this gap with $T_C$ compensation and Mn content, we attribute it to a separation between the valence and Mn-derived impurity bands.

The implications of our work on the understanding of carrier-mediated ferromagnetic exchange in III-Mn-V diluted magnetic semiconductors will be discussed.