NSYSU physics 書報討論

Weekly Seminar

Beyond Equilibrium Limits in Semiconductors: Extreme Doping and Highly Mismatched Alloy Synthesis by Ion Implantation and Pulsed Laser Melting

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Abstract

The electronic and structural properties of semiconductors are fundamentally constrained by limits on *dopant* and alloy incorporation. Heavy doping is essential for applications in low-resistance contacts as well as *plasmonic*, epsilon-near-zero and *thermoelectric* materials. However, in heavily doped semiconductors, the free-carrier concentration often saturates despite continued addition of extrinsic *dopants*. This so-called *doping limit* is closely related to the formation of compensating native defects, whose formation energy and stability depend on the position of the Fermi level in the host semiconductor. Similarly, the synthesis of highly mismatched semiconductor alloys (HMAs) is often restricted by limited solubility, large lattice mismatch, defect formation, and phase separation. In this talk, I will discuss how ion implantation combined with pulsed laser melting (PLM) provides a *nonequilibrium pathway* for overcoming these equilibrium incorporation limits.

As an example, I will first focus on the well-known n-type doping limit of *GaAs*. Donors including S, Si, and Ge were introduced by ion implantation and activated by either rapid thermal annealing (RTA) or PLM. While RTA produces a similar saturation electron concentration of approximately $2\text{-}3 \times 10^{18}\,\mathrm{cm}^{-3}$ for all three *dopants*, PLM transiently melts the implanted layer and enables rapid *epitaxial* regrowth (*in situ*), kinetically trapping *dopants* at high *substitutional* concentrations and producing electron concentrations exceeding $10^{19}\,\mathrm{cm}^{-3}$. Although residual point defects initially reduce carrier mobility, subsequent RTA substantially recovers the mobility while retaining carrier concentrations significantly higher than those obtained using RTA alone.

The second part extends this approach to the synthesis of dilute $\mathrm{GaN}_x\mathrm{As}_{1-x}(x \lesssim 5\%)$, a highly mismatched alloy (HMA) in which small concentrations of nitrogen strongly modify the electronic structure of GaAs. The large chemical and size mismatch between N and As makes nitrogen incorporation challenging under conventional equilibrium growth conditions. Ion implantation followed by PLM provides a route to incorporate nitrogen and form *metastable* dilute GaNAs through rapid liquid-phase *epitaxial* regrowth.

Together, these examples demonstrate that conventional limits on semiconductor doping and alloy composition need not represent absolute materials boundaries. By controlling the kinetic pathway through ion implantation and transient pulsed laser melting, *metastable* semiconductor states with otherwise inaccessible *dopant* concentrations and alloy compositions can be realized, providing new opportunities for electronic and *optoelectronic* materials.

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