p-type Indium Nitride Achieved

Breakthrough in New Solar Cell Material

An MSD team led by Wladek Walukiewicz, using material provided by investigators at Cornell University, has provided compelling evidence that, contrary to earlier reports, one can achieve p-type doping in indium nitride (InN). This discovery suggests that a major barrier to the development of the full range of the III-nitride compound semiconductor family (InN, GaN, AlN and their alloys) has been overcome. These materials can be used for optoelectronic applications ranging from the near infrared to the deep ultraviolet spectral regions.

The electrical properties of a device are dependent on the nature and configuration of the component materials. For example, a junction between n-type (electron conducting) and p-type (hole conducting) materials forms a diode while a properly configured n-p-n or p-n-p arrangement produces a transistor. Control of conductivity is achieved through impurity doping: substitution of a phosphorus atom for a silicon atom produces n-type conductivity (phosphorus has one more electron than silicon); substitution of a boron atom produces p-type conductivity (boron has one fewer electron than silicon).

Mg-doped InN shown to be p-type below surface layer – barrier to LED's, laser diodes, solar cells is overcome.

III-nitride semiconductors have found commercial success in the last 15 years as light emitting diodes and lasers in the green to near- ultraviolet regions of the spectrum. Most of these devices use structures composed of GaN (band gap = 3.4 eV, near ultraviolet) and the alloy $In_xGa_{1-x}N$ (<20%), which extends operation into the visible region of the spectrum. The potential spectral range of $In_xGa_{1-x}N$ alloys was greatly expanded with the discovery that its band gap is only 0.7 eV (near infrared) (MSD Highlight 02-8), rather than the previously-thought of 1.9 eV and this has generated great interest in InN for applications such as high-efficiency solar cells, light-emitting diodes, laser diodes and high-frequency transistors. The ability to fabricate both p-type and n-type InN is essential for the realization of these devices; however, as noted, in a bulk silicon semiconductor, only n-type InN has been reported to date.

The difficulty in producing p-type InN can be understood within a model previously developed by Walukiewicz. In this model, the degree to which a material can be doped n- or p-type depends on the energy levels of the conduction band (empty states) and the valence band (filled states) compared to the average energy of a defect in the crystal (e.g., a dangling bond). The conduction band of InN is unusually low in energy and lies below the average defect energy (see figure). This has two important consequences. First, native point defects, which are present in all semiconductors, are expected to act as donors in InN, which is consistent with the n-type activity reported for all nominally undoped InN samples grown to date. Second, surface defects, which again are found in all semiconductor, will cause the near-surface region to be strongly n-type, regardless of chemical or physical treatments.

Magnesium (Mg) has one fewer electron than Ga; Mg-doped GaN is p-type. Thin film samples of Mg-doped InN appear, however, to be n-type, but further analysis revealed that this effect could be attributed to conduction in the n-type "surface accumulation" layer only. To determine the nature (n-type or p-type) of the InN below the surface, the researchers applied electrical potentials to the surface to "deplete" the accumulation layer in such a way as to access the bulk material below. By performing a "capacitance-voltage" measurement (see figure), definitive evidence of p-type InN was obtained. Further support for p-type doping was obtained by using energetic particle irradiation to generate additional defects to "compensate" for the Mg acceptors; material treated in this way became n-type throughout.

The achievement of p-type doping in InN is a major step toward the fabrication of p-n junctions, and therefore electronic and optoelectronic devices using InN. Future work will concentrate on determining the hole transport characteristics in p-InN and In-rich $In_xGa_{1-x}N$ and on developing device designs that can overcome the challenge posed by the electron surface accumulation layer.

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R. E. Jones, K. M. Yu, S. X. Li, W. Walukiewicz, J. W. Ager, E. E. Haller, H. Lu, and W. J. Schaff, "Evidence for p-type doping of InN," *Phys. Rev. Lett.*, 96, 125505, (2006).

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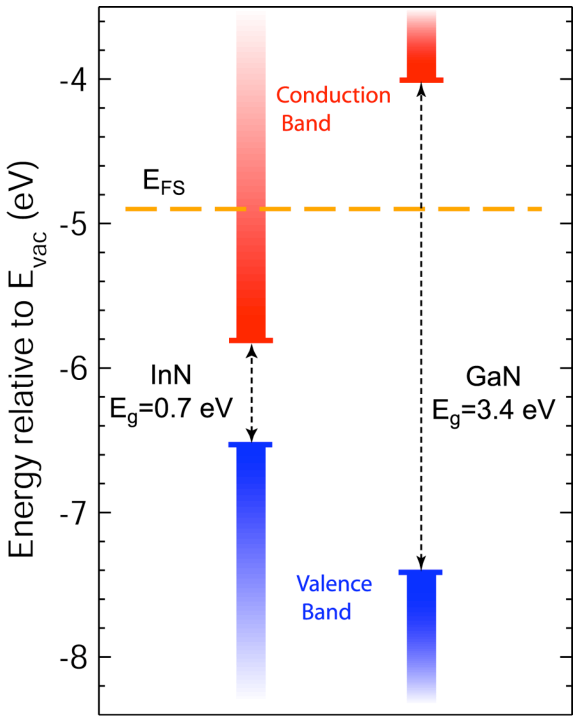
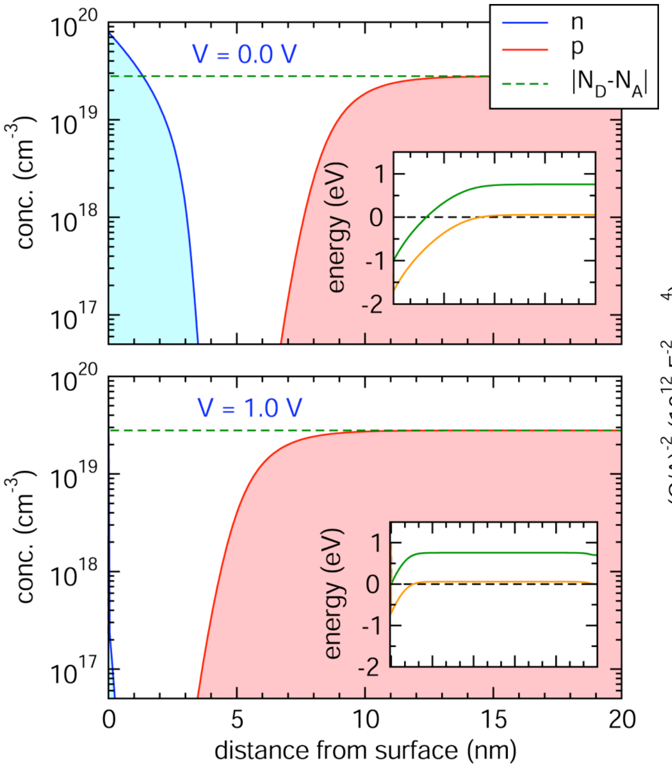
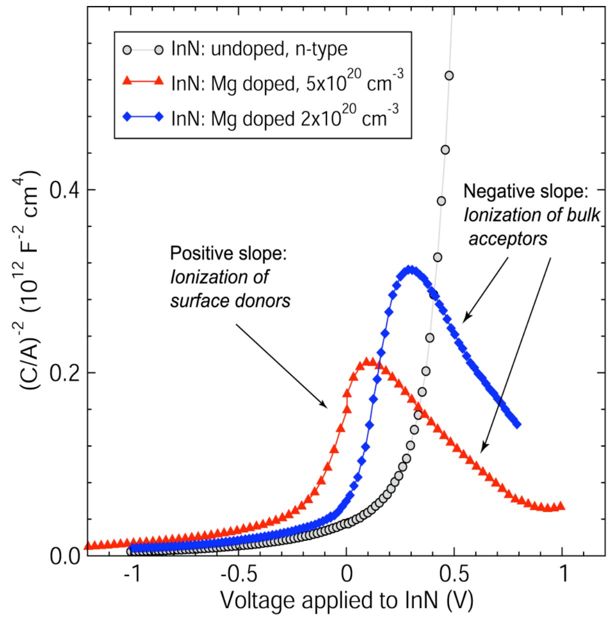


Energy level diagrams** of **InN and GaN. *The average energy of a native defect (dashed line) such as a dangling bond or vacancy (E_{FS}, Fermi stabilization energy) lies 4.9 eV below the vacuum level. This energy level lies within the energy gap of GaN but within the conduction band of InN. As a result, native point defects are donors in InN.*



***Surface inversion layer** in p-InN. The net concentration of Mg acceptors (N_D-N_A) is indicated by the green lines. Defects at the surface are donors, creating a near-surface layer of n-type material (blue shaded area, top graph). By applying positive voltage to the semiconductor with respect to the surface, electrons can be removed from the accumulation layer, bringing the p-type activity close to the surface (red area), where it can be measured electrically.*



***Capacitance-voltage measurements**. The peak and then decrease of capacitance of Mg-doped material is definitive evidence of p-type InN underneath an n-type "surface inversion" layer. Undoped n-type material does not peak.*

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