Emission from GaN p-n Junction Cold Cathodes

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We report electron emission from forward-biased GaN p-n junction cold cathodes. Emission occurs when electrons in a buried n-type layer are injected into a p-type surface layer by applying ~4-5 V to the p-type layer.

A band diagram of the device is shown in figure 1. GaN was grown by MBE onto sapphire substrates. Following an AlN buffer layer, n-type, intrinsic, and p-type layers were grown in succession. The intrinsic and p-type layers were etched to expose the buried n-type layer, creating mesa structures. Electrons can be injected into the p-type layer by applying a positive bias voltage to the top contact. Emission can theoretically occur when the forward bias exceeds the sum of the band gap and the electron affinity, such that the vacuum level lies below the Fermi level as shown in the figure. However many of the electrons injected into the p-type layer will loose some energy to phonons, such that they are collected at the p-type contact and not emitted. The structures built in this work were not optimized for emission efficiency.

The diodes were loaded into a UHV chamber and baked at 200C. Emission currents of a few pA were obtained without additional surface treatment. Reducing the electron affinity by evaporating Cs onto the surface increased the emission current; total emission currents over 200nA can be obtained from devices with 10^{-3} cm^2 area. The electron affinity remains low enough to produce significant emission for several days in UHV. The "true" electron affinity evidently remains positive, since the emission current is a small fraction of the diode current but increases more rapidly than the diode current as the bias voltage is increased.

Energy spectra of the emission are shown in figure 2. The spectra show that some of the emission occurs at energies above the Fermi level in the n-type layer. These electrons are apparently transported to the surface with little or no loss in energy. Most of the emission occurs at energies below E_F. The peak in the energy distribution moves to lower energy as the forward bias is increased. At an applied bias of 5V, the emission extends to 0.9eV below E_F. This lower energy cutoff is in agreement with the vacuum level of the p-type surface, assuming the electron affinity is 1.1eV and the Fermi level in the p-type contact is 3.0V below the conduction band minimum. The peak energy is higher, indicating that a significant voltage drop occurred across the surface of the p-type layer, between the contact at the outer edge and the emission site closer to the center.

Photoemission also occurs. A small peak is visible near 2 eV in the energy spectra. Emission at similar energies occurs when the sample is illuminated with white light, but is removed when the light is filtered to cut off wavelengths below 440nm. Without illumination, the peak appears to be excited by photons created by recombination in the GaN junction.

Figure 3 shows how large electric fields at the diode surface can increase the emission. These measurements were made with a pointed probe anode placed approximately 0.5 mm above the surface. The effect of anode field at anode voltages above ~100V follows a power relationship. The minimum anode voltage needed to collect current is reduced with forward bias.

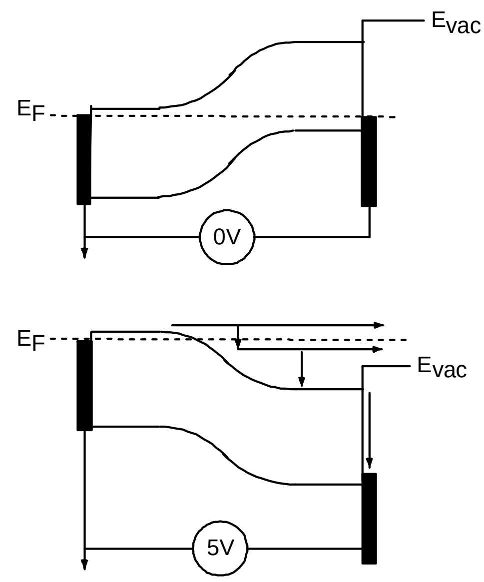

Figure 1. Band diagram of a p-n junction emitter without bias (top) and under forward bias (bottom). The p-type surface layer is shown with small positive electron affinity.

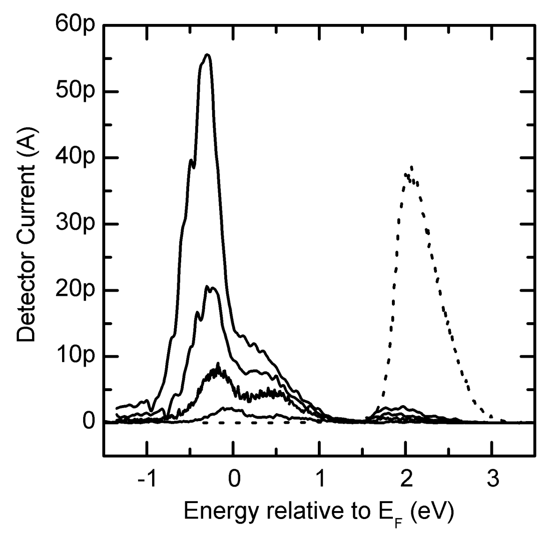

Figure 2. Energy spectrum of the current emitted from a GaN p-n junction. The solid curves were obtained under forward bias of 5.0, 4.75, 4.5, and 4.0V. The dotted line was produced under zero bias with illumination from an incandescent source.

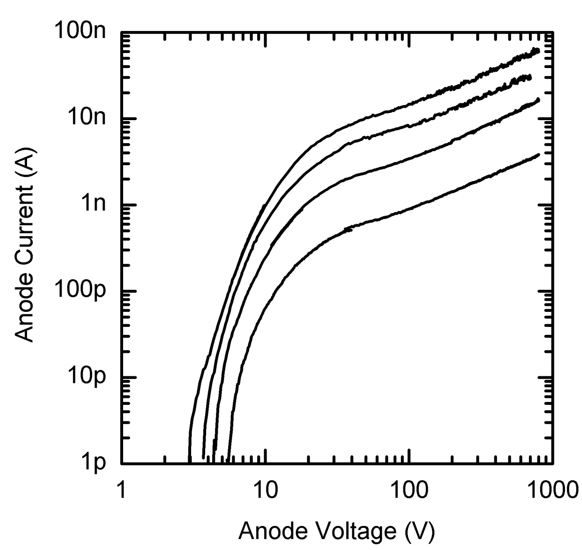

Figure 3. Anode currents collected as a function of anode voltage where the diode bias was 5.0, 4.8, 4.6, and 4.4 V (largest to smallest anode currents).