Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2002	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Electron emission from GaN n p junctions	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory, Washington, DC 20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**3**	

Electron emission from GaN $n-p$ junctions

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(Received 10 May 2002; accepted 20 August 2002)

We report on electron emission from cesiated GaN $n-p$ junctions in forward bias. Surface electric fields ~ 3 V/μm caused a fivefold increase in emission current. Initial maximum currents in excess of 200 nA degrade to 50 nA due to charge trapping but are quickly recovered at zero bias. Energy spectra confirm negative electron affinity 80 h after cesiation, indicate resistive losses limit the emission current, and reveal significant emission at energies above the Fermi level of the injecting contact. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1514824]

The electric potential sustained by a biased junction can be used as a means of raising electrons' energy relative to the vacuum level, causing emission.[1] Cesiated Si[2] and clean SiC[3] junctions emit electrons when reverse biased into avalanche breakdown. Forward biased structures having low or negative electron affinity can emit at lower junction voltages, but so far have not produced significant emission.[4,5] Improved forward biased structures may be possible using GaN, which achieves effective negative electron affinity (NEA) when provided with a surface dipole such as Cs.[6,7] [Effective NEA means the bands are bent down near the surface, such that the vacuum level is below the conduction band minimum (CBM) in the neutral bulk. True NEA requires no band bending.] In addition, the GaN:Cs bond is reported stable to 700 °C.[8] Here we report on the emission properties of forward biased GaN $n-p$ junctions.

The GaN layers used in this study were grown by molecular beam epitaxy on C-plane (0001) sapphire substrates.[9] The layers (not optimized for use as an electron emitter) were: (1) a low temperature AlN buffer, (2) a 2-μm-thick Si-doped n^+ contact (5×10^{18} cm^{-3}), (3) a 0.5-μm-thick nominally undoped layer, and (4) 0.1-μm-thick Mg-doped p^+ contact (10^{18} cm^{-3}). Mesa structures were defined by dry etching, and metal contacts were then applied to the exposed n-type layer. The metal contact to the p-type layer was patterned as a strip encircling the periphery of the mesas, producing diodes with ~ 0.1 mm^2 exposed area.

A chip containing several finished diodes was loaded into an ultrahigh vacuum chamber (base pressure 5×10^{-11} Torr) via load lock and baked at 200 °C (to avoid damage to the metal contacts). Cesium was applied by passing 5.0 A through a 12 mm SAES Cs source held 2 in. above the surface for 15 min; during that time the pressure rose to 1.1×10^{-10} Torr.

Emission measurements were accomplished as described previously,[10] using a hemispherical analyzer with an energy resolution of 0.1 eV. The diode pads were contacted with wire probes. A third wire served as an anode. The anode tip was normally positioned ~ 0.5 mm from the diode and biased 200 V positive with respect to the n-type contact.

A schematic band diagram of the device is shown in Fig. 1. The top diagram shows the diode without applied bias, and the lower diagram shows the band bending expected when a diode voltage V_d and an anode voltage V_a are applied, creating diode current I_d and anode current I_a. As shown in the diagram, we expect that some band bending will occur at the metal contacts, and that the contact band bending will increase when injecting large currents. Electrons from the n-type layer are injected into the conduction band of the

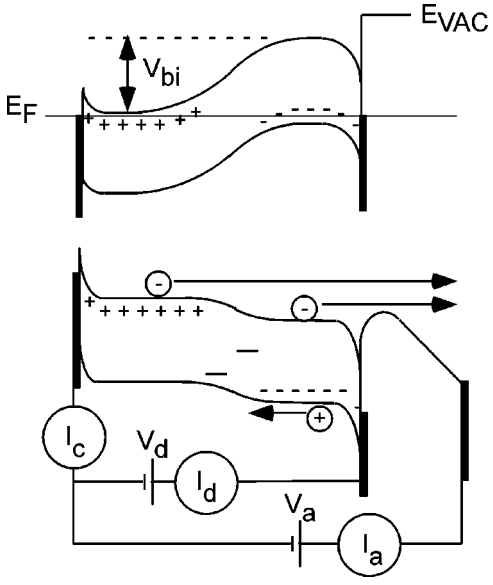

FIG. 1. Energy band diagram of a $p-n$ junction emitter without applied voltage (top) and with positive diode voltage applied (bottom). Indicated are the built-in diode voltage V_{bi}, the cathode current I_c, the diode voltage V_d and current I_d, and the anode voltage V_a and current I_a.

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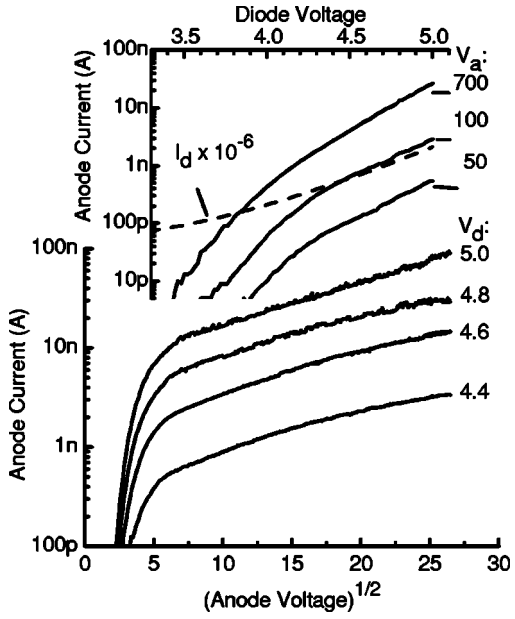

FIG. 2. Current emitted from a cesiated diode, plotted vs diode voltage for several anode potentials and vs anode potential for several diode voltages (measured from the same diode at different times). The dashed line is the diode current$\times 10^{-6}$.

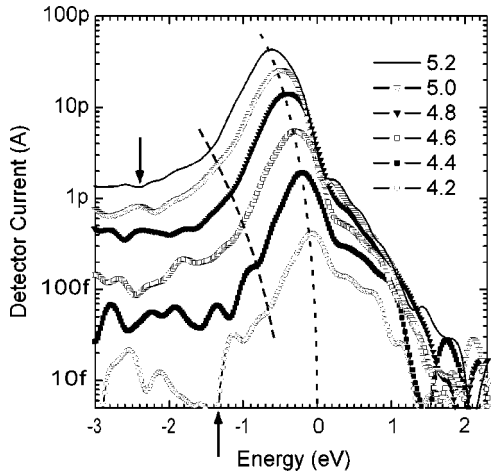

FIG. 3. Emission spectra measured at the forward voltages indicated.

p-type layer when the diode voltage equals the built-in diode potential (slightly less than the band gap). If the surface has zero or negative effective electron affinity, those electrons can be emitted to vacuum, provided they lose no energy as they pass through the surface depletion layer. To the extent that the diode voltage (less the potentials at the contacts and in the p-type layer) exceeds the built-in potential, some of the electrons may arrive at the surface depletion layer with energies above the conduction band minimum. In this case emission can occur with positive effective electron affinities. However, scattering is likely to occur as the charge passes through the diode, reducing the emission efficiency η. Charge trapped in midgap states can alter the band bending and so change the distance the hot electrons must travel, and thus the diode and emission currents.

Before cesiation, diode voltages above 5.0 V produced small but measurable emission currents. At $V_d = 5.5$ V, I_a was typically ~ 1 pA, whereas I_d was ~ 5 mA, making the emission efficiency $\eta \sim 2 \times 10^{-10}$. The emission showed a considerable difference in the increasing vs. decreasing diode voltage sweeps, probably because of charge trapping.

The emission currents measured after cesiation are plotted in Fig. 2. Diode voltages above 3.5 V were sufficient to produce emission. The emission current was very strongly influenced by the electric field created by the anode. Plotting the log of the anode current vs. the square root of the anode voltage (at constant diode voltage) produces a straight line. This suggests that the barrier height V is reduced by the applied field, since $\Delta V = 3.8F^{1/2}$, where V is in volts and F is in V/Å.[11] In this case the pointed anode probe wire was held approximately 0.1 mm above the diode surface. An anode potential of 800 V produces a field at the emitter surface near 10^4 V/cm, which would reduce the vacuum barrier by ~ 0.05 V. This modest change resulted in a factor of 5 increase in emission current for each forward diode voltage.

Energy distributions obtained from a cesiated diode at bias voltages ranging from 4.2 to 5.2 V are shown in Fig. 3. Based on the energy diagram of Fig. 1 and assuming the built-in diode voltage is 3.2 eV, applying 4.2 V across the diode should put the conduction band minimum of the neutral p-type layer 1 eV below E_F. Assuming classical emission (no tunneling), the minimum emission energy should occur at the vacuum level. The 4.2 V spectrum shows a low energy threshold (marked in the figure) at least 1.3 eV below E_F (marked with an arrow in the figure), ~ 0.3 eV below the calculated p-type layer CBM and consistent with effective NEA. This low energy threshold moves exactly 1 eV to more negative values in the other spectra as the bias voltage applied to the diode contacts is increased by 1 V.

Although the low energy thresholds of the emission spectra are consistent with emission from the CBM of the p-type layer, most of the emission occurred at much higher energies. The maximum emission occurred at -0.1 eV in the 4.2 V spectrum, and shifted to -0.6 eV in the 5.2 V spectrum. A more intense low-energy threshold occurred near -0.6 eV in the 4.2 V spectrum and shifted to -1.4 eV in the 5.2 V spectrum. This behavior is somewhat inconsistent with Fig. 1, since one might assume that the electron energy distribution impacting the surface would have peaked closer to the p-type CBM. One likely cause is the quality of the p-type contact and the potential created by the diode current moving laterally through the thin p-type layer from the center portion of the diode to the contact strip at the edge. The potential created by the diode current will be greatest in the center of the diode and much less near the contact. A bulk resistivity on the order of 0.01 ohm cm is sufficient to cause a shift of ~ 1 eV over the surface of the diode; a contact resistance will cause some of the applied diode voltage to be dissipated near the p-type contact. Thus it seems likely that the energy difference between the lowest threshold and the more intense threshold is caused by the potential at the p-type contact. The energy difference between the higher-intensity threshold and the peak is due to the potential distributed across the surface of the diode (caused by resistive loss in the p-type layer). Note that the contact potential appears to be similar in each spectrum whereas the resistive potential increases.

The current passing through the n-type layer is likely to cause a much smaller resistive drop since it is thicker and

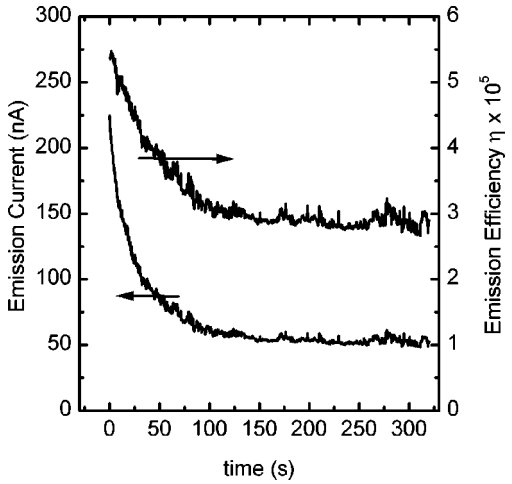

FIG. 4. Emission current and emission efficiency vs time, 80 h after cesiation.

more heavily doped. However, the emission intensity at energies above the peak (near zero) appears to saturate in the spectra measured at 4.6–5.2 V. The apparent saturation is probably caused by resistive losses in the *n*-type layer, moving the entire spectra to slightly lower energies.

Significant emission also occurs well above zero potential. Each of the spectra extends to at least 1.3 eV. These electrons do not appear to reflect a thermal energy distribution, either in the shape or the range of energies. The ''hot'' electron emission appears similar to the high-energy emission that occurs in field emission. During field emission, the hot electrons are thought to gain energy released when states well below E_F, emptied by field emission, are refilled (similar to an Auger process). A similar excitation process would explain the high-energy portions of the spectra in Fig. 3. The energy might be released when electrons injected into the *p*-type layer release large energies in a single scattering event. In the case of field emission from a metal, the energy release must occur within a few nm of the surface if the hot electrons are to escape without suffering an energy loss. Since the emission in this case occurs from GaN, the mean free path is much longer, so the scattering events may occur within the *p*-type or intrinsic layers. In addition, much of the hot electron generation probably occurs near the surface due to recombination there, releasing energy to a high density of electrons still in the conduction band. The recombination is likely to proceed via surface states, releasing much less energy than the bulk band gap. We also visually observed luminescence from some of the diodes due to electron–hole pair recombination. This light caused photoemission near 2 eV, originating at parts of the *p*-type surface not connected to the diode.

Figure 4 shows the emission current and efficiency as a function of time just after the diode voltage was increased from 0 to 5.0 V. The emission current was initially over 200 nA but decayed exponentially to a steady state value near 50 nA. The emission efficiency also decayed, but by less than a factor of two (the diode current also decayed). The initial emission current could be recovered by turning off the diode voltage for several minutes. This behavior suggests that charge is being trapped and released from midgap states within the diode, probably within the intrinsic layer. These measurements were made 80 h after the diode was cesiated, demonstrating the robustness of the surface. The diode voltage was zero during most of that time. Additional tests after 432 h showed the emission current had decayed to less than 5 nA.

In conclusion, we have observed significant emission currents from cesiated GaN diodes in forward bias. A change of 0.6 V in the diode voltage caused a tenfold change in the emission current. The emission spectra show effective NEA was achieved and maintained for several days. Diode currents flowing laterally across the thin *p*-type surface layer as well as contact potentials reduced the actual diode voltage applied to most of the diode surface. The time decay of the emission indicates that deep traps in the GaN also reduced the emission current. The emission current is thus likely to be increased by improving the *p*-type contacts and reducing the lateral distance to the contacts, and reducing the density of trap states.

This work was sponsored by DARPA Contract No. DAAH01-H01-C-R034 and ONR through NRL.

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