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Electron diffusion length and lifetime in *p*-type GaN

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We report on electron beam induced current and current–voltage $(I-V)$ measurements on Schottky diodes on *p*-type doped GaN layers grown by metal organic chemical vapor deposition. A Schottky barrier height of 0.9 eV was measured for the Ti/Au Schottky contact from the $I-V$ data. A minority carrier diffusion length for electrons of (0.2 ± 0.05) μm was measured for the first time in GaN. This diffusion length corresponds to an electron lifetime of approximately 0.1 ns. We attempted to correlate the measured electron diffusion length and lifetime with several possible recombination mechanisms in GaN and establish connection with electronic and structural properties of GaN. © *1998 American Institute of Physics.* [S0003-6951(98)03848-0]

The wide band gap semiconductors GaN and AlGaN are already established materials for light emitting diodes and lasers,[1] and have recently attracted a lot of interest for applications in high power and high temperature electronics.[2] Some of the most significant parameters influencing the design and performance of both unipolar and bipolar high power devices are the critical field for electric breakdown and the transport parameters, such as minority carrier diffusion lengths and lifetimes, for both holes and electrons. Correlation of these parameters with material properties is important for succesful development of power electronics systems based on the nitrides. Minority carrier diffusion lengths and lifetimes are critical parameters for the performance of thyristor switches and other bipolar devices.[3,4] Larger hole lifetimes in the *n*-type standoff layer of thyristors lead to smaller ON-state voltages and therefore smaller power dissipation and larger maximum current densities.[3,4] The electron diffusion length is important because it determines the range of suitable thicknesses for the *p*-type injection layer in bipolar structures. In this study we report a measurement of the electron diffusion length and estimate the electron lifetime as a minority carrier in GaN.

We fabricated Schottky diodes on Mg-doped GaN/sapphire layers grown by metal organic chemical vapor deposition (MOCVD). The experiments were performed on samples from two commercial vendors. For both samples the hole concentration measured by Hall measurements was approximately $(1-4)\times 10^{17}\,\mathrm{cm}^{-3}$, and the hole mobility was approximately 5 $\mathrm{cm}^2/\mathrm{V\,s}$. Prior to metal deposition, the GaN surfaces were cleaned with organic solvents, dipped in HF:H_2O (1:10), rinsed in deionized water, then blown dry with nitrogen gas. Contact metals were sputtered in a chamber with background pressure of 2×10^{-8} Torr and patterned to produce Schottky contacts as well as large-area ohmic contacts. A Ni/Au (200 Å/1500 Å) metallization scheme was used for the ohmic contacts, while Ti/Au was used for the Schottky contacts.

Current–voltage characteristics were measured at room temperature with an HP 4156 parameter analyzer and are shown in Fig. 1. From these measurements we obtained a barrier height of $\Phi_{Bp}=0.9\,\mathrm{eV}$. Since the reported barrier heights of Ti on *n*-type GaN range from approximately 0.1 to 0.6 eV,[5] we may observe that for Ti we obtain $\Phi_{Bp}+\Phi_{Bn}\leqslant 1.5\,\mathrm{eV}$ which is less than the band gap of GaN (approximately 3.4 eV). This discrepancy can be partially accounted for by tunneling of holes through the very thin barrier formed at the contact due to the high Mg acceptor concentration necessary to achieve *p*-type doping, and due to the image force lowering of this barrier.[6] The ideality of the diodes, which we measured to be approximately five, supports the hypothesis of hole tunneling.

Electron beam induced current measurements on the same samples were carried out in a JEOL 6400V scanning electron microscope, using either GW Electronics preamplifier model 103B, followed by GW Electronics Specimen Current Amplifier model 31, or Keithley 486 picoammeter. More details of the experimental procedures, as well as electron beam induced current (EBIC) measurements on *n*-type samples have been published elesewhere.[3,7] When electrons from the electron beam are injected into the semiconductor near a Schottky contact, generation of electron-hole pairs occurs. Due to the large concentration of holes in *p*-type sample compared to the generated electron-hole concentra-

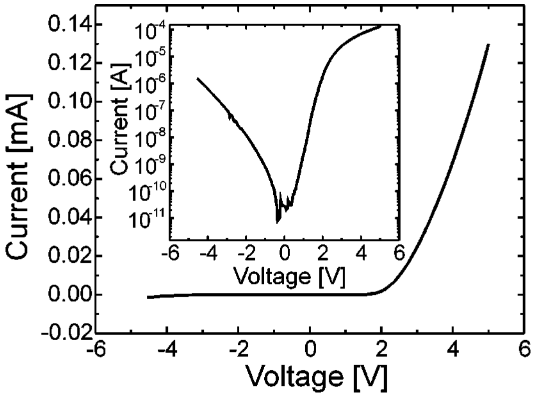

FIG. 1. Current-voltage characteristic of Ti/Au Schottky diode on *p*-type Mg-doped MOCVD-grown GaN. Inset shows the same characteristic on a logarithmic scale.

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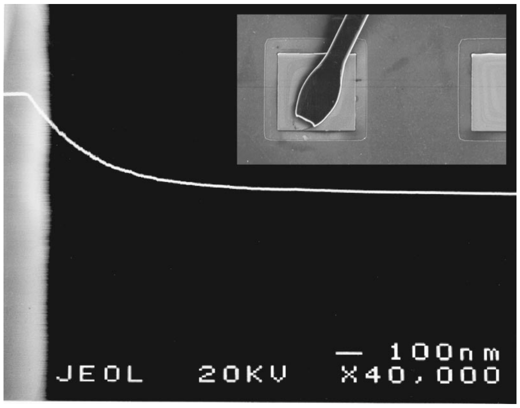

FIG. 2. EBIC line scan profile of MOCVD *p*-type GaN sample superimposed on the secondary electron image of the Ti/Au Schottky contact. The electron beam voltage and current are 20 kV and 0.4 nA, respectively. Inset in the figure (upper right) shows one Schottky device.

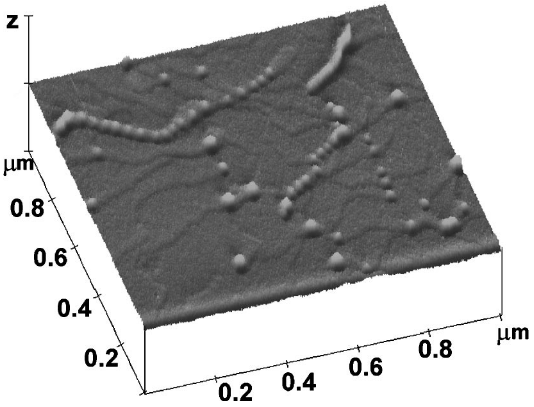

FIG. 3. AFM scan of the surface of MOCVD *p*-type sample shows pits induced by linear dislocations terminated at the surface which occupy boundaries between otherwise defect-free grains.

tion, only electrons are effectively generated, assuming low electron beam currents. This is the reason why a *p*-type sample is required for measurement of electron (as a minority carrier) transport parameters. If the circuit is closed with a lateral ohmic contact on the semiconductor surface, electrons which diffuse close to the Schottky contact generate an induced current. The current follows the law $I = kx^{\alpha}$ exp $(-x/L_e)$ where α ranges from $-1/2$ in case of negligible surface recombination to $-3/2$ in case of large surface recombination. L_e is the electron diffusion length as a minority carrier and x is the distance between the Schottky diode and the injection spot.[8] The minority carrier diffusion length is obtained by fitting the measured $I(x)$ dependence to the theoretical equation. We assume small surface recombination corresponding to $\alpha = -1/2$ since the GaN samples analyzed here have good photoluminescence efficiency. Even if we assumed infinite surface recombination, which is unlikely, the quantitative values do not change more than 25%. The minority carrier lifetime, τ_e, can then be obtained from Einstein's relationship $L_e^2 = D_e \tau_e$, where the diffusivity, D_e, can be calculated from the electron mobility using $D_e = (kT/q)\mu_e$. A typical example of the line scan profile of the EBIC as a function of distance from the edge of the Schottky contact in the case of p-GaN is shown in Fig. 2. To our knowledge, this is the first measurement of electron transport properties as a minority carrier in GaN. The electron diffusion length as a minority carrier of (0.2 ± 0.05) μm was measured for both samples. This value is an average of multiple measurements at different positions on both samples under different values of electron beam current in the range between 0.1 and 1 nA. The electron lifetime as a minority carrier is approximately equal to 0.1 ns, assuming an electron diffusivity of 2.6 $\mathrm{cm^2\,s^{-1}}$ which corresponds to an electron mobility of 100 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$. It is of considerable interest to correlate the observed values of electron transport parameters with the measured electronic and structural properties of the GaN samples. Several different recombination mechanisms might be responsible for the observed electron diffusion lengths and lifetimes. The recombination at traps is one possibility. Our measurements for electrons in *p*-type GaN indicated minority carrier lifetimes approximately two orders of magnitude smaller than the observed value for holes in *n*-type GaN.[7] Since a large concentration of Mg atoms is required to achieve *p*-type doping (due to the relatively deep Mg acceptor level), and since trapping lifetimes are inversely proportional to the number of traps, trapping at Mg atoms can explain why the electron lifetime is two orders of magnitude smaller than hole lifetime measured in *n*-type GaN.[7] The recombination at linear dislocations is another possibility already discussed in case of n-GaN and hole lifetimes.[7] We performed extensive structural characterization of the surfaces of GaN samples analyzed here using atomic force microscopy (AFM) to establish the possible effects that linear dislocations and other defects may have on transport properties. Linear dislocations are known to induce pits on the surface which can be measured by AFM.[9] On most of the AFM images, we observed that linear dislocation-induced pits are located at boundaries between otherwise defect-free grains. The size of grains was in the range between 0.3 and 0.5 μm. A typical example for this is shown in Fig. 3. If recombination at linear dislocations indeed occurs,[10] it would limit diffusion lengths to subgrain size length, in agreement with our measurements.

In conclusion, electron transport properties as a minority carrier were measured on MOCVD grown GaN samples, using EBIC measurements of Ti/Au Schottky diodes. The barrier height of Ti/Au contact was 0.9 eV. The average value for the diffusion length is 0.20 μm which corresponds to lifetime of 0.1 ns given electron diffusivity D_e of 2.6 $\mathrm{cm^2\,s^{-1}}$. The same samples were also structurally characterized by AFM, and the size of the defect-free regions surrounded by linear dislocations is found to be in the 0.3–0.5 μm range. Two possible explanations of the observed values of electron transport parameters are recombination at Mg related traps or recombination at linear dislocations, but does not exclude other recombination mechanisms.

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