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Enhanced electroluminescence from the fluorine-plasma implanted Ni/Au-AlGa_N/Ga_N Schottky diode

B. K. Li,¹ M. J. Wang,² K. J. Chen,² and J. N. Wang^{1,a)}

¹*Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong 852, China*

²*Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong 852, China*

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The effect of fluorine-plasma (F-plasma) implantation on the current-voltage (*I-V*) and electroluminescence (EL) characteristics of Ni/Au-AlGa_N/Ga_N Schottky diodes have been investigated. The observed EL spectrum is dominated by the Ga_N near band edge emissions. The threshold current of the EL emission for F-plasma implanted diodes is significantly lower than that for the previously reported diodes without the F-plasma implantation. This reduction of threshold current results from the presence of negatively charged F-centers in AlGa_N layer which leads to upward band bending of AlGa_N layer and enhanced hole injection by multi-step tunneling process through AlGa_N layer. The magnitude of the upward banding in AlGa_N layer is estimated to be 0.36 eV by analyzing the forward-biased *I-V* characteristics. © 2011 American Institute of Physics. [doi:10.1063/1.3622643]

Two-dimensional electron gas (2DEG) related electroluminescence (EL) from a forward biased Ni/Au-AlGa_N/Ga_N Schottky diode has been observed and studied.¹ A model based on the Fermi-level (E_F) depinning caused by current (hot electrons) induced interface states' ionization explains the hole injection processes and the observed EL characteristics. Meanwhile, the fluorine-plasma (F-plasma) implantation technique can effectively incorporate negatively charged F ions into AlGa_N barrier, depleting the 2DEG in the channel of AlGa_N/Ga_N high electron mobility transistors (HEMT) and convert the device from depletion-mode (D-mode) into enhancement-mode (E-mode).^{2–5} Deep-level transient spectroscopy (DLTS) (Ref. 6) and photoconductivity^{7,8} studies have revealed that the F-centers in AlGa_N/Ga_N heterostructure are deep electron traps. The negatively charged F ions, when incorporated in the AlGa_N barrier layer, can effectively modulate the energy band profile, and consequently, introduce significant modification (e.g., enhancement) to the hole injection processes critical to the EL characteristics in the Ni/Au-AlGa_N/Ga_N Schottky diode.

In this work, we report the effect of F-plasma implantation on the current-voltage (*I-V*) and EL characteristics of the Ni/Au-AlGa_N/Ga_N Schottky diode. EL emission from the Ga_N layer was observed, indicating that the holes are injected into the Ga_N layer. It was found that the threshold current for EL emission was reduced remarkably with F-plasma implantation. According to the hot electron induced Fermi-level depinning model,¹ these results provide further evidence for the concept of energy band modulation by the negatively charged F ions. Furthermore, the tunneling injections of holes are enhanced due to the existence of F-centers in AlGa_N layer. Based on an analysis of the forward-biased *I-V* characteristics, the upward band bending of AlGa_N

layer due to negatively charged F ions is determined to be 0.36 eV.

The device structure of the F-plasma implanted Ni/Au-AlGa_N/Ga_N Schottky diode is schematically shown in Fig. 1(a). The device fabrication procedure is the same as that for fabricating the un-implanted devices,¹ except that the Schottky contact area was implanted with the F-plasma (CF₄) at 150 W for 120 s prior to the deposition of the Schottky metal. *I-V* measurements were performed using a HP4155A semiconductor parameter analyzer. A He-Cd 325 nm laser was used as the excitation source for photoluminescence (PL) measurements. A Keithley 6221 current source was used to drive the Schottky diode for the EL measurements. A pulsed-current with a 10% duty cycle and a frequency of 87 Hz was selected to avoid heating effect.

Figure 1(b) shows the *I-V* characteristics of the Ni/Au-AlGa_N/Ga_N Schottky diode with and without the F-plasma implantation measured at 20 K. Beyond the turn-on voltage marked as V_{tr} and V_t , a “kink” labeled as V_{t3r} indicating the existence of additional turn-on voltage can be clearly identified in *I-V* curve of the un-implanted Schottky diode, while no “kink” can be identified from that of the F-plasma implanted device. To uncover the existence of additional conduction channels in the F-plasma implanted Schottky diodes the differential resistance dV/dI is calculated. As indicated in Fig. 1(c), two additional turn-on voltages V_{t2} and V_{t3} can be clearly identified in the dV/dI -*V* curve of the F-plasma implanted Schottky diode, while the voltage V_{t3r} marked in the dV/dI -*V* curve of the un-implanted diode corresponds to the “kink” in the *I-V* curve.

When the applied bias is higher than V_{t2} , EL emission from the F-plasma implanted Schottky diode is observed. The EL and the PL spectra measured at 20 K are shown in Fig. 1(d). The EL was driven by a pulsed current of 13 mA ($V = 3.95$ V). When measuring the PL spectrum, the laser was focused on the Schottky area. Similar with that of the

^{a)}Electronic mail: phjwang@ust.hk.

FIG. 1. (Color online) (a) Schematic device structure of the F-plasma implanted diode. (b) I - V curves of the un-implanted (dashed line) and F-plasma implanted (solid line) diodes. (c) Calculated dV/dI vs applied bias of the un-implanted (dashed line) and F-plasma implanted (solid line) diodes. V_{t3r} , V_{t2} and V_{t3} correspond to the voltages at which dV/dI begins a fast decrease. (d) EL (solid line) and PL (dashed line) spectra of the F-plasma implanted diode. All the data shown in this figure are measured at 20 K.

un-implanted device, the excitonic emissions from GaN layer dominate in both the EL and PL spectra, indicating that the holes are injected into GaN layer. Therefore, V_{t2} and V_{t3} identified in the dV/dI - V curve correspond to the turn-on of different hole injection processes. In PL spectrum, the main peaks originating from free and bound exciton emissions in GaN layer are labeled as FXA, FXB, and DX, respectively, while in the EL spectrum, the peaks are labeled correspondingly as FXA_{2DEG-h} , FXB_{2DEG-h} , and DX_{2DEG-h} , respectively.

It is natural to assume that the model of the Fermi-level depinning at Ni-AlGaIn interface¹ also applies to the F-plasma implanted Ni/Au-AlGaIn/GaN Schottky diode. However, as the F-plasma implantation induces negatively charged centers in AlGaIn layer,^{3,8} the band diagrams of the F-plasma implanted diode at zero and forward bias will be different from that of the un-implanted device. Fig. 2(a) shows the schematic band diagram of the F-plasma implanted diode at zero bias with the negatively charged F ions induced additional band bending in the AlGaIn layer indicated.³ Fig. 2(b) shows the schematic band diagram of the F-plasma implanted diode at forward bias beyond V_t . In this bias region, due to the negatively charged F ions mainly concentrated in the top region of AlGaIn layer,^{2,3} the upward band bending of AlGaIn layer is much larger in the F-plasma implanted device than that in the un-implanted one. As the forward bias and/or current increases, the interface states are ionized by the injected hot electrons leading to the Fermi-level depinning. As the depinned metal Fermi-level moves downwards it will first align with the valence band edge of the GaN layer and the holes are injected from the metal into GaN layer by tunneling through AlGaIn layer (process (i) in Fig. 2(b)). With the applied bias and/or device current further increased more interface states are ionized and the metal Fermi-level moves further down. Due to the enhanced band bending in AlGaIn layer, the holes can tunnel into the va-

FIG. 2. (Color online) Schematic band diagrams of the F-plasma implanted Ni/Au-AlGaIn/GaN Schottky diode, (a) at zero bias, and (b) at bias far beyond the turn-on voltage. See the main text for detailed discussion about ϕ_B , ϕ_B' , and hole injection processes.

lence band of AlGaIn layer followed by drift into the GaN layer (process (ii) in Fig. 2(b)). With even further increasing applied bias and/or device current, more interface states are ionized and the metal Fermi-level moves closer to the valence band of AlGaIn layer. As labeled as process (iii) in Fig. 2(b), the hole starts to be injected from the metal Fermi-level into the AlGaIn valence band by thermionic emission followed by drift into the GaN layer.

In the F-plasma implanted diode, the hole tunneling current are expected to be significantly enhanced by the F-centers assisted multi-step tunneling channels in AlGaIn layer.⁹⁻¹¹ Furthermore, for the hole injection process (ii), the effective thickness of AlGaIn layer for hole tunneling from metal into the valence band of AlGaIn is reduced due to the enhanced band bending. This will also lead to an enhancement of the hole tunneling current. On the other hand, the two tunneling processes (i) and (ii) cannot be well separated in I - V characteristics because of the small band offset between valence bands of AlGaIn and GaN.¹² Therefore, the additional turn-on voltage V_{t2} observed in the dV/dI - V curves corresponds to the turn-on of tunneling hole injection processes, while V_{t3} corresponds to the thermionic emission hole injection process.

For the un-implanted diode, self-consistent band profile calculation shows that the band bending in AlGaIn layer reaches a relatively flat band condition and will not bend further with increasing applied voltage in our studied bias region.¹ In contrast, for the F-plasma implanted diode as schematically shown in Fig. 2(b), the band bending of AlGaIn at forward bias beyond V_t is significantly large. This upwards band bending in AlGaIn lifts up the energy bands of GaN. As a result, much less interface states need to be ionized for the turn-on of tunneling hole injection process in the F-plasma implanted diode in comparison with that in the un-implanted diode. This is expected to lead a decrease of threshold current for EL emission in the F-plasma implanted

FIG. 3. (Color online) EL intensity vs diode current curves of the un-implanted (open triangle) and F-plasma implanted (open circle) diodes. The inset shows the EL intensity vs applied bias curve of the F-plasma implanted diode. The solid line is a guide for eyes. The arrow marks a deviation from the line at 3.45 V.

diode. The magnitude of the upward band bending induced by the negatively charged F ions in AlGaIn layer can be estimated by calculating the “effective Schottky barrier height” ϕ_B' at zero bias condition. As shown in Fig. 2(a), ϕ_B' corresponds to the energy difference between metal Fermi-level and the energy maximum of the upward bended conduction band minimum of AlGaIn layer.³ At room temperature, the transport mechanism of the Schottky diode is dominated by thermionic emission processes, and the Schottky barrier height can be extracted from the forward I - V characteristics.^{13,14} It was found that the ϕ_B' is 1.68 eV for F-implanted Schottky diode, while the ϕ_B is 1.12 eV for the un-implanted diode. This indicates that the Schottky barrier height “effectively” becomes 0.56 eV larger after the F-implantation. A recent study of x-ray photoelectron spectroscopy has shown that the Schottky barrier height ϕ_B between Ni and AlGaIn/GaN exhibits an increase of 0.2 eV after the F-plasma implantation.¹⁵ Therefore, the magnitude of upward band bending ($\phi_B' - \phi_B$) at zero bias condition is obtained to be $0.56 - 0.2 = 0.36$ eV. This upward band bending of 0.36 eV in AlGaIn layer lifts up the energy bands of GaN layer, while the increase of ϕ_B 0.2 eV relatively lowers the metal Fermi-level. Both effects result in much less interface states being ionized in order to align the metal Fermi-level and valence band maximum of GaN layer, consequently lead to a decrease of the threshold current for EL emission in the F-plasma implanted diode.

Figure 3 shows the EL intensity versus diode current (EL- I) characteristic of the F-plasma implanted diode measured at 20 K together with that of the un-implanted diode. It can be clearly seen that the threshold current for EL emission has been reduced by about an order of magnitude with the F-plasma implantation. This is consistent with our model described above. The turn-on and/or the operation voltages for the EL emissions, on the other hand, are similar for diodes with and without F-plasma implantation. This indicates that the external EL efficiency of the Ni/Au-AlGaIn/GaN Schottky diode can be significantly improved by F-plasma implantation.

The inset of Fig. 3 shows the corresponding EL intensity versus applied bias (EL- V) characteristics of the F-plasma implanted diode measured at 20 K in logarithmic scales. As it is shown a transition voltage at 3.45 V can be identified. This transition voltage is consistent with the additional turn-on voltage V_{t3} in the dV/dI - V curve. When $V < 3.45$ V, the hole injection is dominated by the tunneling processes, while the thermionic emission process starts to play a role when applied bias above 3.45 V. The identification of different proposed hole injection processes, i.e., tunneling and thermionic emission, in transport behaviors as well as in EL- V characteristics further verifies that the Fermi-level depinning model applies to the F-plasma implanted Ni/Au-AlGaIn/GaN Schottky diode.

In conclusion, the negatively charged F-centers in AlGaIn induce an additional band bending that leads to a significant reduction of the threshold current for EL emission and enhance the hole tunneling current from the depinned Ni/Au Fermi-level into the GaN layer in an F-plasma implanted Ni/Au-AlGaIn/GaN Schottky diode. The external EL efficiency of the diode is significantly improved by F-plasma implantation. The studies of EL emission from the un-implanted and/or F-plasma implanted Ni/Au-AlGaIn/GaN Schottky diodes present a novel type of UV light emitting diode (UV-LED), of which fabrication processes are embedded in the D-mode and/or E-mode AlGaIn/GaN HEMT technologies. Therefore, this type of UV-LED can be easily integrated into the AlGaIn/GaN HEMTs based devices or integrated circuits, and novel optoelectronic applications can be developed.

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