Sub-Bandgap Laser Light-Induced Excess Carrier Transport Between Surface States and Two-Dimensional Electron Gas Channel in AlGaN/GaN Structure

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Abstract—Variations of the channel resistance of an AlGaN/GaN high electron mobility transistors caused by subsequently incident photons with sub-bandgap energies after ultraviolet light-induced changes became stable were studied. Temperature-dependent measurements yielded a 0.342 eV thermal activation energy and wavelength-varying measurements yielded a 0.8 eV cut-off photon energy. The ratio between the two values is very close to the theoretical value of the ratio between the valence and conduction band discontinuities. A qualitative description about the transports of excess carriers through the band discontinuities, is also proposed and consistent with the experimental results.

Index Terms—Optical modulation, optoelectronic devices, piezoelectric semiconductor.

I. INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) have been the subject of intense research since the demonstration of the first GaN based transistor. [1] The large breakdown electric fields and high electron mobilities in GaN materials have propelled significant progresses in fabricating HEMTs with higher performance. [2], [3] The presence of piezoelectric polarization field at the AlGaN/GaN interface causes the accumulation of electrons near the interface, which is referred as a two-dimensional electron gas (2DEG) layer. Positively charged surface states are simultaneously induced at the sample surface to maintain the charge neutrality of the sample. [4] Variations of the positively charged surface states cause the 2DEG electron density to change and have been used in various sensor applications. [5]-[7] These surface states were reported to cause current collapse problems during the operation of HEMTs and can be removed by passivated the surface by a thin layer of SiO$_2$ or Si$_3$N$_4$ [8], [9].

Light-induced variations of 2DEG have been previously observed when studying the current collapse occurred in AlGaIn/GaN HEMTs [10], [11]. Illumination of photons with sub-bandgap energies decreased the channel resistance between source and drain electrodes of AlGaN/GaN HEMTs [10]. Ultraviolet (UV) light illumination also decrease the channel resistance was also reported in another report [11]. In this research, experimental results taken at different temperatures and with different excitation wavelengths are presented and a complete theoretical model related to surface states are proposed. This proposed model indicates that UV-induced excess carriers in the 2DEG channel are able to reach the surface after overcoming the band discontinuities and is consistent with the experimental results.

II. EXPERIMENTS

The sample used in this study is an AlGaN/GaN HEMT structure grown with a metal-organic chemical vapor deposition (MOCVD) reactor. First, a thick intrinsic GaN thin film (2 μm) was grown on a c-plane (0001) sapphire substrate followed by the growth of another lightly Mg-doped p-GaN layer (50 nm) as the insulating layer. On top of the insulating layer, another 0.3 μm thick intrinsic GaN layer and 5 nm thick intrinsic Al$_{0.35}$Ga$_{0.65}$N layer were subsequently grown. The top capping layer was a 30 nm thick n-type Al$_{0.35}$Ga$_{0.65}$N layer. Mobility and sheet carrier concentration of the 2DEG at the AlGaN/GaN interface were measured 412 cm$^2$/V-s and 2.07 × 10$^{13}$ cm$^{-2}$, respectively. The source and drain electrodes were formed by evaporating Ti/Al (50 nm/150 nm) layers and ohmic contacts were obtained after alloying the metal layers in 650°C for 30 seconds in nitrogen. The width of the electrode and the distance between the electrodes were 700 μm and 800 μm, respectively. Excess carriers were induced by the light output from an UV lamp (365 nm, intensity $I_0 = 58.20 \mu W/cm^2$). Variation of the channel resistance was achieved by illuminating the sample with another continuous (CW) green laser light (532 nm, 5 mW) or a pulsed tunable laser light (1000 nm–2000 nm, 5 Hz. Pulse energy $\sim 2.5 \mu J$). Schematic illustration of the experimental setup and the sample structure are shown in Fig. 1. A constant current of 10 mA was provided by a source meter for both the CW and pulsed experiments. The channel
III. RESULTS AND DISCUSSION

A decrease in the channel resistance (∼50 Ω) was observed when the device was illuminated with UV light because of the creation of excess carriers, shown in Fig. 2. UV-induced resistance change reached an equilibrium value after several hundreds of second. A subsequent illumination of another green laser light caused the channel resistance to slightly increase (∼3.5 Ω), shown in the inset of Fig. 2. After the termination of the green laser illumination, the channel resistance quickly returned to its original level.

In order to understand the origin of the resistance variations, measurements were taken at 6 different temperatures, shown in Fig. 3. The decrease of the resistance after the termination of green laser light was faster at higher temperatures, which suggested that the resistance recovery is a thermal-activated process. This process was analyzed using an Arrhenius plot (insets of Fig. 3), which describes the decay time constants (τ) at different temperatures. The temperature dependence of τ can be described as

\[ \tau = \tau_0 \exp[\Delta E/kT] \]  

where ΔE is the thermal activation energy. The least square fit to the data resulted in a thermal activation energy ΔE of 0.342 ± 0.018 eV. This result indicates thermal energy of 0.342 eV is required for the resistance recovery process to occur. It should be noted that the straight fitting line in the inset of Fig. 3 indicated that the systematic error should not be a problem in despite of the narrow temperature range.

In addition, the channel resistance increases were also investigated when subsequently illuminated with photons with different photon energies. The amount of resistance increase became smaller with the decreasing excitation photon energies and no channel resistance increase was observed when illuminated with photon energy smaller than ∼0.8 eV, shown in Fig. 4. Noted the pulse energy of the excitation laser is approximately 2.5 mJ and remains a constant when the laser wavelength is between 1050 nm and 1950 nm. It should be also noted that the induced resistance change in Fig. 4 is two-order of magnitudes smaller than the change in Fig. 3 because of the nanosecond pulsed laser used in the experiment. This indicated that a 0.8 eV energy barrier exists when describing the mechanism that causes the channel resistance to increase. The subsequently incident photon provides the required energy to overcome this barrier and increase the channel resistance. Noted that the ratio between 0.8 eV and 0.342 eV is very close to the commonly accepted ratio of 7:3 between conduction band and valence band discontinuities at AlGaN/GaN interfaces. [12] The bandgap of AlGaN was measured to be [13]

\[ E_g = xE_g(\text{AlN}) + (1-x)E_g(\text{GaN}) - x(1-x) \]
where $E_g(\text{AlN}) = 6.13$ eV and $E_g(\text{GaN}) = 3.42$ eV at room temperature. The conduction band discontinuity for the AlGaN/GaN interface was estimated to be [12]

$$\Delta E_C = 0.7 [E_g(x) - E_g(0)]$$  \hspace{1cm} (3)$$

According to (2) and (3), the conduction band discontinuity ($\Delta E_C$) was calculated to be 0.50 eV and the valence band discontinuity ($\Delta E_v$) was about 0.22 eV. These two theoretical values and the ratio between them were both very similar to the obtained values from the experiments, which indicated the two energy barriers obtained from the experimental results is closely related to the conduction and valence band discontinuities.

From the experimental results, a qualitative description to explain the observed channel resistance variations is proposed. The band diagram of the AlGaN/GaN heterostructure without any illumination was shown in Fig. 5(a). Illumination of UV light generates excess electron–hole pairs in the AlGaN/GaN interface. Excess holes are able to overcome the valence band discontinuity after absorbing enough thermal energy. These holes are subsequently swept into the surface due to the internal electric field and captured by the neutral-charged surface states. This process decreases the number of trapped electrons in the surface states, which is shown in Fig. 5(b). Thermal energy from the ambient is not high enough for the UV-induced excess electrons to overcome the conduction band discontinuity at the AlGaN/GaN interface, which is higher than the valence band discontinuity. However, the conduction band discontinuity can be overcome by absorbing another photon from the subsequent CW green or pulsed tunable laser light, whose photon energies are both higher than the conduction band discontinuity. These electrons are captured by the positive-charged surface states after entering the surface region and reduced the number of positive-charged surface states. This leads to a higher channel resistance, shown in Fig. 5(c). After the termination of the CW or pulsed laser light, excess holes slowly returned to the surface after absorbing enough thermal energy, which is similar to the mechanism shown in Fig. 5(a). The channel resistance returns to its original value prior to the subsequent laser illumination.

The proposed explanation not only is consistent with the models previously proposed other groups [10], [11] but also the experimental results in this study. Experimental results from pulsed tunable laser measurements indicated the existence of a 0.8 eV barrier for the mechanism that causes the channel resistance increase, which is referred as the conduction band discontinuity (0.50 eV) between the AlGaN/GaN interfaces. Measurements under different temperatures revealed that an energy barrier of 0.342 eV presented, which is referred as the valence band discontinuity (0.22 eV) between the AlGaN/GaN interfaces. In addition, the ratio between 0.8 eV and 0.342 eV is very similar to the ratio between 0.5 eV and 0.22 eV, which strongly support the validity of the proposed model. The proposed explanation and experimental results reveal complex carrier dynamics occur at the AlGaN/GaN interface and are not previously observed. UV-induced excess electrons cause the trapped electrons in the surface states to increase after absorbing subsequently incident photons. Thermal energy helps the excess hole to reaches the surface and reduces the number of trapped electron in the surface states. These two processes are competing processes and whether the channel resistance increases or decreases depends on the competition between these two processes.

**IV. Conclusion**

The channel resistance increases of AlGaN/GaN HEMTs caused by subsequently incident photons with sub-bandgap
energies after ultraviolet (UV) light-induced changes became stable were studied. Measurements taken at different temperatures revealed that an energy barrier of 0.342 eV exists for the resistance to decrease. The resistance increase became smaller with decreasing photon energies and exhibits a cut-off energy barrier of 0.8 eV. A qualitative description to explain the relationship between the surface states and UV-induced excess carriers was proposed. Excess electrons and holes generated in the 2DEG channel are able to reach the surface after overcoming the conduction and valence band discontinuities, respectively. Injection of these excess carriers changes the charged surface state density and causes the variations of the channel resistance. The proposed explanation is consistent with the experimental results. This study demonstrates the abilities to optically modulate the surface states and is beneficial for future developments of AlGaN/GaN high electron mobility transistor devices.

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REFERENCES


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