Effect of Proton Irradiation on 2DEG in AlGaN/GaN Heterostructures

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Abstract. Low temperature Hall effect measurements were carried on AlGaN/GaN micro-Hall effect sensors before and after irradiation with 380 keV and fluence of $10^{14}$ protons/cm² protons. The sheet electron density after irradiation did not show significant changes but there was a dramatic decrease in the electron mobility of the heterostructures. Prior to irradiation, the observation of well-defined Landau plateaus in the Hall resistance and Shubnikov-de Haas oscillations (SdH) at 4.5 T was indicative of the high quality the heterojunction confining the two-dimensional electron gas (2DEG) at the AlGaN/GaN interface of micro-Hall effect sensors. In contrast, the Landau plateaus disappeared after irradiation and the threshold magnetic field required for the observation of the SdH increased, which was accompanied by a decrease of the electron mobility. Temperature dependent magnetoresistance measurements were used to deduce the effective mass and the quantum scattering time before irradiation. A negative magnetoresistance was observed at low magnetic fields which is related to weak localization and parabolic negative magnetoresistance attributed to electron-electron interaction in both samples.
1. Introduction

Hall Effect magnetic sensors based on III-nitrides are promising for applications in space technology and other such harsh environments. Such applications necessitate device operation at high temperatures and under harmful radiation. Specifically, AlGaN/GaN Hall effect sensors are excellent candidates for measuring magnetic fields in such environments [1].

At low temperatures, three kinds scattering in the AlGaN/GaN heterostructure are dominant: interface roughness, alloy disorder [2] and impurity scattering [3]. Reports show a constant sheet density from room temperature to low temperature, and temperature independent mobility at very low temperature [4-6].

Redwing et al. have reported quantum Hall effect AlGaN/GaN heterostructures to exhibit clear Landau plateaus at a mobility of 7500 (cm$^2$/Vs) [5] and Wang et al. for mobilities exceeding $10^4$ (cm$^2$/Vs) [7]. Shubnikov-de Haas oscillations are used to determine the effective mass and quantum scattering times, which give valuable insights into the dominant scattering mechanisms in the two-dimensional electron gas 2DEG [8-10].

The effect of proton irradiation on the quantum Hall effect in AlGaN/GaN micro-Hall sensor is not clear despite being an important area of research for ‘hard-electronics’ for devices used in space and other such environments. Here, we describe the results of a systematic study on the magnetotransport and quantum Hall effect of AlGaN/GaN micro-Hall sensors before irradiation and after proton irradiation. This study showed the existence of the 2DEG layer even after irradiation and stability of the sheet electron density but significant degradation of the mobility after irradiation.

2. Experimental.

The AlGaN/GaN micro-Hall effect sensors were grown by MOCVD on sapphire substrates. The structures consisted of a 2μm GaN layer, a 25 nm unintentionally doped Al$_{0.25}$Ga$_{0.75}$N layer and Ti/Al/Ni/Au Ohmic contacts. Samples were irradiated with 380 keV protons at a fluence of $10^{14}$ protons/cm$^2$ at the Takasaki Ion Accelerators for Advanced Radiation Application. Van der Pauw measurements were carried out from 5K to room temperature, with a 100μA drive current for non-irradiated samples and 30μA for irradiated ones. The magnetoresistance measurements were performed in a cryogenic liquid helium cryostat from 1.6 to 300$^\circ$K with magnetic fields of up to 10 T produced by a superconductor magnet.

The room temperature electron mobilities were 2324 cm$^2$/Vs and 1627 cm$^2$/Vs for non-irradiated and irradiated samples, respectively.
3. Results and Discussion

As shown in Fig. 1, the sheet electron density before and after irradiation was stable over all the temperatures studied with a slight increase near room temperature (RT). The increase of the sheet electron density at RT maybe due to the thermal activation of bulk carriers. Since the sheet electron density is inversely proportional to the absolute sensitivity according to the equation \( S_A = \frac{1}{qN_S} \) we conclude that the absolute sensitivity is stable over this range of temperature after irradiation. The sheet resistance shown in Fig. 2, increased with increasing temperature for both samples, which is related to the decrease of the mobility as shown in Fig. 3.

![Figure 1](image1.png)  
**Figure 1.** Temperature dependence of the sheet density of the AlGaN/GaN before and after irradiation.

![Figure 2](image2.png)  
**Figure 2.** Temperature dependence of the sheet resistance of the AlGaN/GaN before and after irradiation.

![Figure 3](image3.png)  
**Figure 3.** Temperature dependence of the mobility of the AlGaN/GaN before and after irradiation.

Rate of change of mobility can be divided in three regions: (1) lower than 90 °K the mobility is almost constant in this region, with the three probable scattering mechanisms being interface roughness, alloy disorder, and impurities scatterings. Ling *et al.* report on the observation of a change in the surface roughness of a GaN layer after proton irradiation due to impurities or point defects [11]. Increases in
interface roughness and/or impurities near the AlGaN/GaN interface can lead to a dramatic decrease in the mobility after irradiation. (2) An intermediate region where the aforementioned scattering are less pronounced and acoustic phonon scattering begins to dominate. (3) At room temperature, where interface roughness and impurity scatterings can be neglected and optical phonon scattering dominates, which explains the decrease of the rate of change of the mobility near room temperature.

Figure 4 shows the quantum Hall resistance of the micro-Hall sensor before and after irradiation. The sample before irradiation showed clear Landau plateaus, which started to disappear at 14°C. After irradiation, the Landau plateaus disappear and the Hall resistance becomes linear but this result does not necessarily mean the absence of the 2DEG.

The origin of the Landau levels is due to the 2DEG edge transport at low temperature, electrons can move freely along the interface without scattering which give constant Hall resistance and the magnetoresistance tends to zero. But increases in electron scattering at the interface can deflect electrons to the bulk and this effect explains the disappearance of the Landau levels and increases of the magnetoresistance. This is the reason why the magnetoresistance increased after irradiation as shown Fig. 5.

The decrease of the minima in the oscillations indicates the absence of parallel conduction. The oscillations are clear from magnetic fields of about 4.5 T before irradiation and from about 8 T after irradiation. This increase in the threshold magnetic field is due to the reduction of the mobility after irradiation.

The Landau levels also disappeared with increasing temperature and drive currents. The temperature dependence of the quantum Hall resistance is shown in Fig. 6 and the current dependence of the Hall resistance in Fig. 7, where the disappearance of the Landau plateaus in this case is due to electron heating phenomenon [12].

Figure 4. Quantum Hall resistance as a function of magnetic field for AlGaN/GaN micro-Hall sensor before and after irradiation.

Figure 5. The magnetoresistance as a function of magnetic field for AlGaN/GaN micro-Hall sensor before and after irradiation.
Both the non-irradiated and irradiated showed weak localization for magnetic fields less than 1T, and a linear dependence of the magnetoresistance as function of square of the magnetic field, as shown in Fig. 8 for a sample before irradiation, which is related to electron-electron interaction according to the equation (1):

$$\rho_{xx} \approx \rho_0 - \rho_0^2 (1 - \mu^2 B^2) \delta \sigma_{xx}^{ee}(T)$$

(1)

where $\rho_{xx}$ represent the magnetoresistivity, $\rho_0$ is the resistivity at zero magnetic field, $\mu$ is the mobility and $\delta \sigma_{xx}^{ee}(T)$ is the correction term due to electron-electron interaction at different temperatures.

Temperature-dependent SdH oscillations are shown in the Fig. 9 for a non-irradiated sample. The oscillations became more pronounced at higher magnetic fields and tended to damp with increasing
the temperature. The oscillating portion of the magnetoresistance can be expressed as:

\[
\frac{1}{2} \frac{\Delta R_{xx}}{R_0} = 2 \frac{\chi}{\sinh(\chi)} \exp\left(\frac{-\pi}{\omega_c \tau_q}\right) \cos\left(\frac{2\pi \Delta E}{\hbar \omega_c} - \pi\right)
\]  

(2)

where \(\omega_c = eB/m^*\) is the cyclotron frequency, \(m^*\) the effective mass at the Fermi level, \(\tau_q\) the quantum scattering time, \(\chi = 2\pi^2 k_B T/\hbar \omega_c\).

\[ \text{Figure 9. Shubnikov de Haas oscillations at different temperature values.} \]

The inset shows oscillating component of the magnetoresistance

We determined the effective mass from the temperature dependence of the oscillating component amplitude, shown in the inset of Fig. 9 at a fixed magnetic field. The amplitude \(A\) of the SdH can be given by:

\[
\ln\left(\frac{A}{T}\right) = C - \frac{2\pi^2 k_B m^*}{\hbar B} T
\]  

(3)

where \(C\) is a temperature independent term, by plotting \(\ln(A/T)\) versus \(T\) we deduce directly the effective mass from the slope which is equal to \(2\pi^2 k_B m^*/\hbar B\).

And in order to obtain the quantum scattering we plot the equation

\[
\ln\left(\frac{1}{4} \frac{\Delta \sinh (\chi)}{R_0 \chi}\right) = C - \frac{m^*}{\hbar \tau_q} \frac{1}{B}
\]  

(4)

The effective mass of the sample before irradiation is approximately 0.20\(m_e\) at 6.3 Tesla. And the quantum scattering time equal to 63.8fs a value close to those reported before [6,13]. The classical scattering time \(\tau_c\) is experimentaly determined from the mobility using the equation \(\mu = e\tau_c / m^*\) and it is approximately equal to 1.38ps. The ratio \(\tau_c/\tau_q\) can give us an idea about the scattering dominant in our device.

Hsu and Walukiewicz [14] propose that only a ratio value between 1.5 and 9 allows dominant scattering in the 2DEG AlGaN/GaN and in this case short range scattering mechanism such
as interface roughness scattering dominate. In our case the ratio is equal to about 21 a value reported before [6]. It remains to be confirm the ratio $\tau_c/\tau_q$ and then the scattering dominant in the dominant scattering in the irradiated sample.

4. Conclusion

We investigated the effect of high energy and high fluence proton irradiation on magnetoelectric properties of AlGaN/GaN micro-Hall sensors from 5.4°K to room temperature. The sensors show good resistance versus the irradiation translated by the stability of the sheet density therefore the stability of the absolute sensitivity of the sensor. However, the proton irradiation damaged the electrical properties of the sensor indicated by the dramatically decrease of the mobility at low temperature by rate of about 81% at 5.4°K. The existing of the 2DEG system either after irradiation with high energy was confirmed by investigation the magnetotransport measurements at low temperature and which show Shubnikov de Haas oscillations at high magnetic field. Damping of the Shubnikov de Haas oscillations and disappearance of Landau plateaus after irradiation were related to the degradation in the mobility causing by increasing the scattering at the interface.

5. References

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