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# Magnetotransport measurement of effective mass, quantum scattering time, and alloy scattering potential of polarization-doped 3D electron slabs in graded-AlGaN

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By applying the technique of polarization bulk-doping in graded AlGaN, it has been possible to create high-mobility three-dimensional electron slabs. Such 3D electron slabs are observed to exhibit clearly resolved Shubnikov de-Haas oscillations. From a temperature-dependent study of the oscillations, we measure the effective mass ($m^* = 0.21 m_0$) and the quantum scattering time ($\tau_q = 0.3$ ps) of carriers in the slabs. An analysis of the ratio of quantum and classical scattering times with the scattering mechanisms leads to the *first direct measurement* of the alloy scattering potential in the AlGaN system ($V_0 = 1.8$ eV).

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**1 Introduction** We recently demonstrated [1] the realization of polarization-doped 3D electron slabs (3DES) in graded AlGaN/GaN heterostructures. This is depicted schematically in Fig. 1a. Grading of $Al_xGa_{1-x}N$ grown epitaxially on GaN causes a non-vanishing polarization in the growth direction, which causes a fixed polarization charge ($N_\pi^D = \nabla \cdot \boldsymbol{P}$). The fixed charge distribution attracts free carriers resulting in the formation of a mobile 3DES. Such 3DES carriers do not freeze out at low temperatures as opposed to traditional shallow donor-doped carriers. There is a large improvement in the low temperature mobility due to the reduction of ionized impurity scattering, resulting in high mobilities of $\mu \approx 3000$ cm$^2$/V s at a carrier density $n_{3d} = 10^{18}$ cm$^{-3}$ for $T \leq 20$ K. As shown in [1] by capacitance-voltage profiling, the carriers are observed to be indeed three-dimensional, caused by the fixed polarization background charge.

We have observed clearly resolved Shubnikov de-Haas oscillations in such polarization-doped 3DES. Analysis of the temperature-dependent oscillations enables us to measure the electron effective-mass, the quantum scattering time, and most importantly, the alloy scattering potential in AlGaN.

**2 Experiment** The sample (Fig. 1a) is a Ga-face structure grown along the polar c(0001) axis by plasma-induced MBE [2] on a MOCVD-grown semi-insulating [3] GaN on a sapphire substrate. The top 100 nm of the structure is linearly graded AlGaN; the composition of Al is changed from 0–30% by controlling the aluminum flux by a computer program [1]. The 3DES formed by polar-

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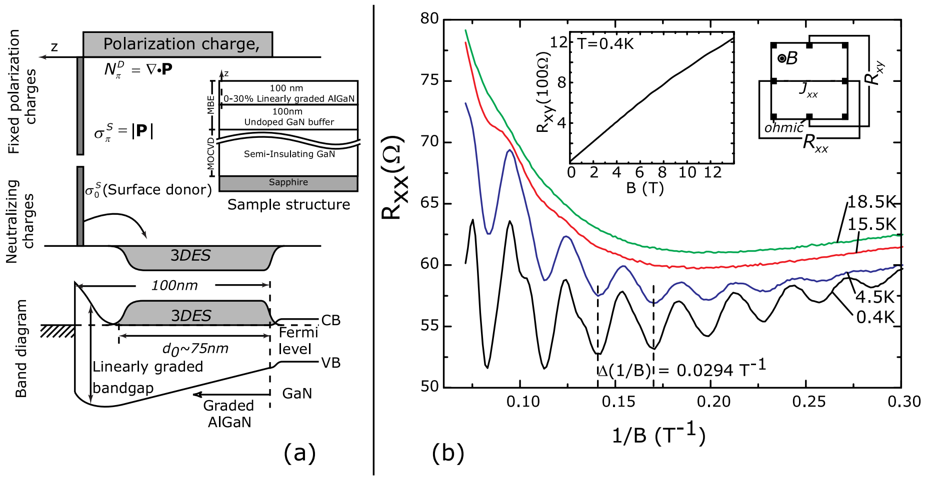

**Fig. 1** (online colour at: www.interscience.wiley.com) Part (a) shows the fixed polarization charge, the mobile 3DES, and the schematic band-diagram with the sample structure used for the experiment. Part (b) shows the measured Shubnikov de-Haas oscillations in $R_{xx}$ against $1/B$ with insets of the Van-der Pauw geometry used and the $R_{xy} - B$ plot for 0.4 K. The oscillations are periodic with a period $\Delta(1/B) = 0.0294\ \mathrm{T}^{-1}$.

ization doping has a temperature-independent electron *sheet*-density $n_{2d} = 7.5 \times 10^{12}\ \mathrm{cm}^{-2}$ and a mobility $\mu = 2700\ \mathrm{cm}^2/\mathrm{V\ s}$ at $T = 20$ K, measured by conventional low-$B$ field Hall measurement.

For magnetotransport measurements of the 3DES, ohmic contacts were formed in a Van-der Pauw geometry (Fig. 1b inset). The sample was immersed in a $^3$He low-temperature cryostat with a base temperature of 300 mK. Magnetic fields in the range $0\ \mathrm{T} \le B \le 14\ \mathrm{T}$ were applied. $R_{xx}$ and $R_{xy}$ was measured as in the geometry depicted in the figure using the standard low-frequency lock-in technique. Magnetotransport measurements were carried out by Link et al. at WSI, Munich.

Figure 1b shows the measured $R_{xx}$ against $1/B$ for four temperatures. The inset is the geometry of contacts and a plot of measured $R_{xy}$ against $B$ for $T = 0.4$ K. The Hall mobility determined from the slope of the $R_{xy}$ curve is $\mu_H \simeq 3000\ \mathrm{cm}^2/\mathrm{V\ s}$, and the Hall 3-D carrier density is $n_{3d} \sim 10^{18}/\mathrm{cm}^3$.

The oscillatory component of the transverse magnetoresistance component $\Delta R_{xx}$ is given by [4]

$$\Delta R_{xx}^{\mathrm{osc}} = \frac{\chi}{\sinh \chi}\, \mathrm{e}^{-\pi/\omega_c \tau_q} \left(\frac{\hbar\omega_c}{2\varepsilon_F}\right)^{1/2} \cos\left(\frac{2\pi\varepsilon_F}{\hbar\omega_C}\right), \tag{1}$$

where $\chi = 2\pi^2 k_B T/\hbar\omega_c$, $\omega_c = eB/m^*$ is the cyclotron frequency, $\tau_q$ is the quantum scattering time, and $\varepsilon_F = \hbar^2 k_F^2/2m^*$ is the Fermi-energy with $k_F = (3\pi^2 n_{3d})^{1/3}$. This is periodic in $1/B$, as is seen in Fig. 1b.

The $R_{xx}$ oscillation period $\Delta(1/B) = 2e/\hbar(3\pi^2 n_{3d})^{-2/3} = 0.0294\ \mathrm{T}^{-1}$ (Fig. 1b) gives a 3-D carrier concentration $n_{3d} = 1.1 \times 10^{18}\ \mathrm{cm}^{-3}$, which is in close agreement with the carrier density inferred from the classical Hall and C-V measurements. For finding the effective mass and quantum scattering time, a FFT-filter is used to remove the background resistance in Fig. 1b, and only the oscillatory part is retained.

**2.1 Effective mass** The effective mass of carriers is determined by fitting [5] the measured amplitude damping of $\Delta R_{xx}$ with temperature at fixed $B$ to the temperature-damping term of Eq. (1), $\chi/\sinh \chi$. From the fit (shown in Fig. 2a), the effective mass is found to be $m^* = 0.21 m_0$. The band-edge electron effective mass in pure GaN (AlN) is $m^*_{\mathrm{GaN}} = 0.20 m_0$ ($m^*_{\mathrm{AlN}} = 0.32 m_0$) [6]. From a linear interpolation for the 3DES experiencing an average Al-composition of $\langle x \rangle = 0.11$ we expect an effective mass of $0.21 m_0$, which is in good agreement with the measured value.

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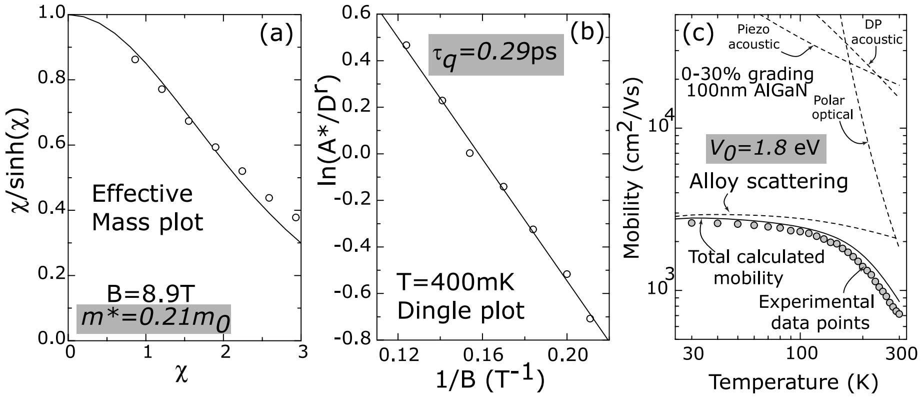

**Fig. 2** Part (a) is the effective mass plot yielding the effective mass of $m^* = 0.21 m_0$. Part (b) is the Dingle plot yielding a quantum scattering time of $\tau_q = 0.3$ ps. Part (c) shows the measured and calculated mobility as a function of temperature. The effect of alloy scattering is seen to be rather strong for the entire temperature range; the reduction in mobility at high temperatures results from optical phonon scattering combined with alloy scattering. Other scattering mechanisms do not contribute strongly to the mobility.

**2.2 Scattering time–quantum and classical** From Eq. (1), the slope of the Dingle plot [7] (Fig. 2b), i.e., $\ln [A^*/(\sqrt{\hbar\omega_c/2\varepsilon_F}\chi/\sinh \chi)]$ ($A^*$ stands for peak values of the oscillation) plotted against $1/B$ yields a quantum scattering time of $\tau_q = 0.29$ ps. An averaging of the quantum scattering times over a range of low temperatures yields a value $\tau_q^{\text{av}} = 0.3$ ps.

**2.3 Alloy scattering potential** Alloy scattering is identified as the dominant scattering mechanism at low temperatures, and is rather strong even at high temperatures. Alloy scattering potential $V_0$ is of a short range nature, which makes the scattering process isotropic and the ratio of classical [8] and quantum scattering times $\tau_c/\tau_q \sim 1$, as observed. The scattering rate due to alloy disorder with a short range potential $V_0$ for a degenerate 3DES is given by [9]

$$\frac{1}{\tau_{\text{alloy}}} = \frac{2\pi}{\hbar} V_0^2 \Omega(x)\, x(1-x)\, g_{3D}(\varepsilon_F)\,, \tag{2}$$

where $\Omega_0(x)$ is alloy composition-dependent volume of the unit cell over which the alloy scattering potential $V_0$ is effective, and $x$ is the alloy composition. $g_{3D}(\varepsilon)$ is the 3-dimensional density of states. Since the alloy is graded Matheissen's rule is used for a spatial averaging of the scattering rate

$$\langle \tau_{\text{alloy}}^{-1} \rangle = \frac{1}{x_0} \int_0^{x_0} \tau_{\text{alloy}}^{-1}(x)\, \mathrm{d}x\,, \tag{3}$$

where $x_0 = 0.225$ is the alloy composition experienced by 3DES electrons at the top edge of the depletion region. Using this simple result we calculate mobility as a function of temperature for the 3DES. This is shown along with the measured temperature-dependent mobility in Fig. 2c. We conclude that to achieve a low-temperature transport mobility of 3000 $\text{cm}^2/\text{V s}$, an alloy scattering potential of $V_0 = 1.8$ eV is necessary. Due to the lack of experimental values, it has been common practice to assume the scattering potential to be the conduction band offset between the binaries forming the alloy ($V_0 = \Delta E_c = 2.1$ eV for AlN, GaN) [6]. With an alloy scattering potential of $V_0 = 2.1$ eV, the calculated mobility is *much lower* ($\approx 2000\ \text{cm}^2/\text{V s}$) than the measured value. The 3DES mobility is dominated by alloy scattering and all other scattering mechanisms are removed, making it a clean measurement of the alloy scattering potential. This report presents the *first measurement* of the alloy scattering potential in AlGaN material system.

**3 Conclusions** In summary, we observe Shubnikov de-Haas oscillations of a degenerate 3DES realized by the novel technique of polarization bulk-doping in graded AlGaN layers. The effective mass of electrons in the graded AlGaN layer was measured from temperature dependence of oscillations to be ($m^* = 0.21m_0$) and their quantum scattering time was measured to be ($\tau_q = 0.3$ ps). Alloy scattering was identified as the dominant scattering mechanism (and confirmed from the measured ratio of classical and quantum scattering times), making it possible to measure the alloy scattering potential ($V_0 = 1.8$ eV).

Degenerate three-dimensional electron gases have many applications such as the study of collective phenomena (spin-density waves, Wigner crystallization, and integral and fractional quantum-Hall effects in 3-dimensions [10]). Polarization-doped electron slabs provide a novel technique of creating such electron populations, overcoming the thermal freezeout effects associated with *impurity-doped* semiconductors. The wide *tunability* of slab thickness and electron density offered by polarization-doping makes it an attractive system for the study of dimensionality and confinement on carrier transport.

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