Mobility and Sheet Charge in High-Electron Mobility Transistor Quantum Wells From Photon-Induced Transconductance

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***Abstract*— When a high-electron mobility transistor is illuminated, the absorbed photons excite electron–hole pairs. The generated pairs are separated by the built-in field in such a way that the electrons end up in the quantum well generating a photocurrent, while together with the holes that are swept toward the gate, they generate a surface photovoltage. Here, we define the photon-induced transconductance as the ratio between the surface photovoltage and the 2-dimensional electron gas (2DEG) photocurrent under identical illumination conditions. We show that this ratio directly yields the channel mobility and the 2DEG sheet charge density. The photocurrent and photovoltage may vary with the wavelength of the exciting photons. We examine and analyze the optical spectra of this photon-induced transconductance obtained from an AlGaN/GaN heterostructure for a range of photon energies showing that the mobility is obtained only for excitation at photon energies above the wide bandgap energy. The method offers an optical alternative to Hall effect and to field-effect mobility. Unlike Hall effect, it may be measured in the transistor itself. The only alternative that can measure mobility in the transistor itself measures field-effect mobility, while the proposed method measures the same conductivity mobility as measured by Hall effect.**

***Index Terms*— Electron mobility, sheet charge density, 2D electron gas, high electron mobility transistor.**

I. Introduction

THE main application of the high electron mobility transistor (HEMT) today is radio frequency (RF) and power switching [1], [2]. Its main advantage over other field effect transistors is in its low channel resistance that results from its high electron mobility and high sheet charge concentration [3]. Optimization of these parameters has been a central design issue that relies on characterization, with Hall effect being the prevalent method [4], [5]. In most cases, the measurements are carried out either on bare wafers [6], [7] or on a dedicated van der Pauw test structures but seldom on the transistor itself [8]. However, fabrication processes often intentionally alter the sheet charge, and, as a result, the mobility changes as well. For example in GaN-based devices, certain passivation coatings are used to increase the density of surface states, which in turn, increase the density of charge in the 2-dimensional electron gas (2DEG) [9]–[11]. These changes may vary among different transistors on the same wafer. Measuring mobility in the transistor has so far been limited to measuring the *field-effect mobility* that has been shown to be prone to errors especially in devices having extreme electron mobilities [12].

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II. Method

To describe the method, we will use a specific example of the AlGaN/GaN structure, but the same applies to most other HEMT structures. Figure 1 shows a schematic band diagram of the AlGaN/GaN heterojunction. The top surface on which the illumination impinges is the AlGaN surface. It has surface states and surface charge trapped in these states. Above-bandgap illumination generates electron-hole pairs. Pairs generated within the AlGaN layer are separated by the built-in electric field in the layer. They are swept to the two sides of the AlGaN layer forming a photovoltage in the layer. Electrons swept into the triangular quantum well at the AlGaN/GaN interface increase the 2DEG charge density and give rise to the observed *channel photoconductivity*. The channel photoconductivity is a product of the number density of the optically generated excess electrons, Δn_s, and the 2DEG electron mobility, μ. Using Ohm's law, we can express the relation between the observed photocurrent, ΔI_D, and the voltage, V_{DS}, applied between the source and the drain:

$$\Delta I_D = V_{DS} q \mu \Delta n_s \frac{W}{L} \quad (1)$$

where q is the electron charge, and W and L are the width and length of the channel, respectively. Note that since the resistor is a quantum well, its resistivity is defined using sheet charge density rather than the common 3D charge density: $\frac{1}{R} = \frac{\sigma A}{L} = q\mu \frac{\Delta n}{d} \cdot \frac{dW}{L}$, where d, the thickness of the well, cancels out. Equation (1) is a product of known constants and two unknowns, the mobility, and the optically generated 2DEG charge. To separate this product to its constituents, one has to know the value of one of the unknowns. In the commonly used Hall effect method, the charge density is obtained from the Hall voltage [13]. In our proposed method, we obtain it from the *surface photovoltage*.

The AlGaN layer may be viewed as a parallel-plate capacitor, to which plates two equal sheet charges of opposite signs were added (the 2DEG on the one side and the surface states

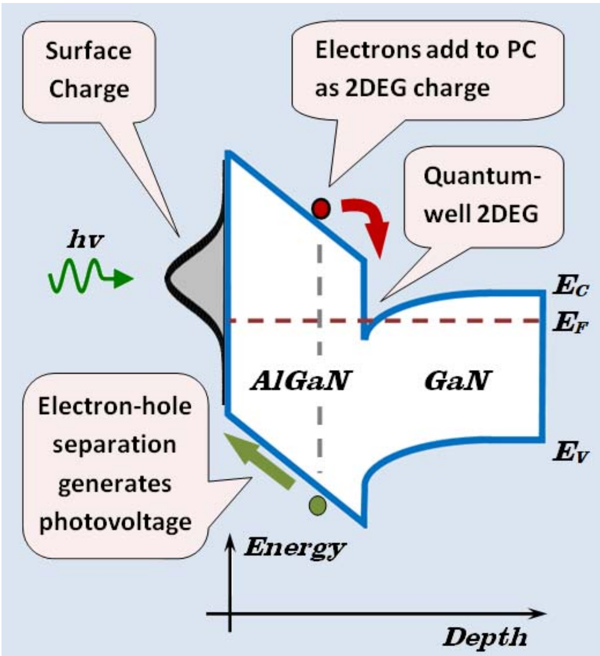

Fig. 1. Schematic band diagram of an AlGaN/GaN heterosctructure. Optically generated electron-hole pairs in the AlGaN layer are separated by the built-in field. Electrons are emitted into the quantum-well, adding to the 2DEG sheet charge. Holes are swept to the surface generating surface photovoltage.

on the other). The induced change in the sheet charge should be equal to the change in the electrical displacement across the AlGaN capacitor (Gauss law):

$$q\Delta n_s = \varepsilon_{AlGaN}\frac{\Delta\Phi_{BB}}{t_{AlGaN}} \quad (2)$$

where ε_{AlGaN} is the dielectric constant of the AlGaN, t_{AlGaN} is the thickness of the AlGaN layer, and $\Delta\Phi_{BB}$ is the surface photovoltage, or the illumination-induced change in the AlGaN band-bending. Since $\Delta\Phi_{BB}$ is the illumination-induced change in the voltage between the gate and the source, and ΔI_D is the illumination-induced change in the drain current, their ratio is an *illumination-induced transconductance*:

$$g_m^{OPT} = \frac{\Delta I_D}{\Delta\Phi_{BB}} = \varepsilon_{AlGaN} V_{DS}\mu\frac{W}{Lt_{AlGaN}} \quad (3)$$

In Eq. (3), all the parameters are known constants except for the mobility. Once we obtain the mobility, we use Eq. (1) replacing ΔI_D and Δn_s with the dark current, I_D, and the dark sheet charge density, n_s, respectively, to obtain n_s:

$$n_s = \frac{I_D L}{V_{DS} q\mu W} \quad (4)$$

To excite electron-hole pairs in the AlGaN layer, one has to illuminate with photons of energy exceeding the AlGaN bandgap. If the AlGaN layer were thick, all photons would be absorbed in the AlGaN and none would reach the GaN. However in the typical GaN HEMT, the AlGaN is ~20 nm, which is over an order of magnitude smaller than the reciprocal of the absorption coefficient [14]. Hence, photons do reach and get absorbed in the GaN layer, as is commonly observed in optical responses of the structure [15]. To eliminate the contribution of the GaN layer to the photocurrent and to the photovoltage, we need to subtract the photo-responses of the GaN bandgap instead of subtracting the dark current and dark voltage. This means that we need to illuminate at two wavelengths, one – slightly below the AlGaN bandgap, and the other – above it. We then subtract the two photocurrent responses to obtain the net AlGaN photocurrent and subtract the two photovoltage responses to obtain the net AlGaN photovoltage.

To use the method, only two photon energies are actually required. However, for an appropriate selection of the energies, we scanned the photon energies over the range between 3.7 and 4.4 eV to obtain spectra of the channel photocurrent and the surface photovoltage. In both the photocurrent and photovoltage spectra, the photo-response of the AlGaN was observed to start about 0.2 eV below the bandgap due to electro-absorption (the Franz-Keldysh effect) [16] and the values at that photon energy ($E_g - 0.2eV$) were used as the reference "dark" values.

In the following sections, we will show results measured on AlGaN/GaN HEMT transistors. It should be noted that since this method does not make any use of the transistor gate, it may be used on a "gateless" device as well. The method may be applied to a range of heterojunctions, wherein the wide gap side is a nanoscale thin layer having a built in field, which direction will sweep electrons into the potential well and sweep holes away from it. These conditions are met in most undoped AlGaN/GaN HEMTs and III-V modulation doped field effect transistors (MODFETs). Under the relevant adjustment, the same may also apply to the rare case of hole confining potential well junctions. The method may be applied to a heterojunction having two Ohmic contacts to the junction, as long as the channel formed between these contacts is conductive. The source of the charge enabling this conduction is not important. For example, it may be surface states, as in the case of undoped AlGaN/GaN, or delta doping, as in the case of III-V modulation-doped field-effect transistor (MODFET). An important strength of this method is in its independence on photon flux variations. As long as the two measurements, photovoltage and photocurrent, are carried out under identical illumination conditions, the effect of photon flux variations cancels out, when the photocurrent is divided by the photovoltage (Eq. 3)

III. Experiment

The $Al_{0.25}Ga_{0.75}N$(20nm)/Fe-doped GaN(2μ m) structure was grown on SiC (CREE Inc.). Mesas were dry etched in chlorine-based plasma. After removal of the GaN cap layer, 100 nm of Si_3N_4 was deposited by plasma enhanced chemical vapor deposition (PECVD). Contact pads and 3 μm wide gate trenches were dry etched in Si_3N_4. All the metal contacts were deposited using e-beam thermal evaporation. The source and drain Ohmic contact layer sequence was Ti(30nm)\Al(70nm)\Ni(30nm)\Au(100nm) annealed at 900 °C for 1 min in nitrogen ambient. The gate contact was a Ni(30nm)/Au(100nm) Schottky barrier. Spectral illumination and electrical measurement were carried out inside a dark Faraday box at atmospheric room temperature conditions.

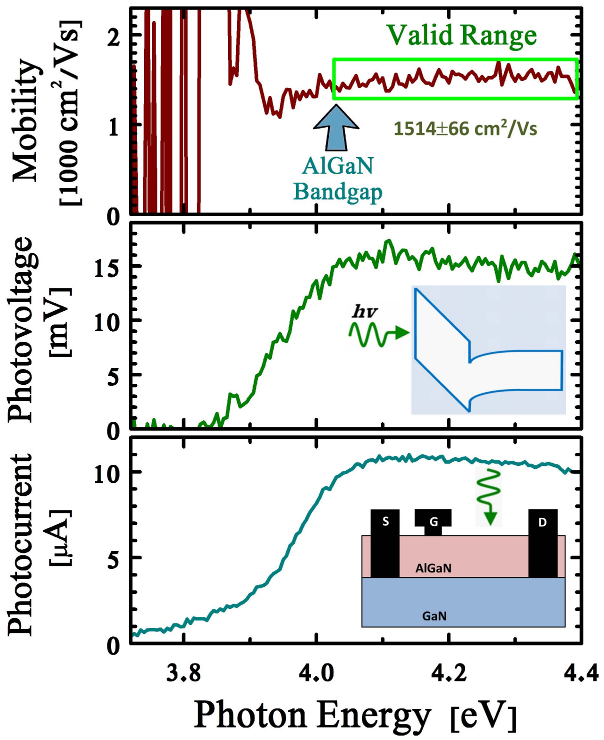

Fig. 2. Photocurrent (bottom panel), photovoltage (middle panel), and the resulting electron mobility spectrum (top panel) in AlGaN/GaN HEMT structure. Insets show the device structure (bottom) and the corresponding band diagram (middle panel) indicating the direction of the illumination.

For illumination, we used a 300 Watt Xe light source. The light was monochromitized using a Newport Corporation double MS257 monochromator followed by order-sorting long-pass filters. The power level of the light source was 6.5 μ W/cm^2 at 280 nm. During spectral acquisition, a constant voltage of 0.1 V was applied between the source and drain contacts. Current measurements were carried out using a Keithley 2400 source-meter. Surface photovoltage was measured using a Kelvin probe (Besocke Delta Phi GmbH). Details of the method have been given elsewhere [7]. Photovoltage and photocurrent were obtained in the same setup under identical illumination conditions. Hall effect measurements were carried out on van der Pauw structures fabricated simultaneously with the transistors on the same wafer and in the same process.

IV. Results and Discussion

Figure 2 shows the photocurrent (bottom panel), photovoltage (middle panel), and the resulting electron mobility spectrum (top panel) in AlGaN/GaN HEMT structure. It shows that the obtained mobility varies around an average value. These variations appear to be the result of the signal-to-noise ratio in the photovoltage spectrum. In the range preceding the AlGaN bandgap, the noise is amplified to extreme values due to a division by (nearly) zero. However, following the AlGaN bandgap the value becomes constant and is valid for mobility assessment. Averaging the values above the AlGaN bandgap and using the standard deviation as the measurement error, we obtained an electron mobility of $\boldsymbol{1514 \pm 66\ cm^2/V{\cdot}s}$. Once we have the mobility, the 2DEG sheet-charge density, n_s, may be readily obtained from the dark value of the current. We calculated a value of $\boldsymbol{6.94 \pm 0.31 \cdot 10^{12}\ cm^{-2}}$ for a dark current value of 1.68 mA. The two insets show the device structure and band diagram indicating the direction of illumination. For comparison, Hall effect measurements carried out on van der Pauw structures yielded an electron mobility of $\boldsymbol{1545 \pm 27\ cm^2/V{\cdot}s}$ and a 2DEG sheet-charge density of $\boldsymbol{6.53 \pm 0.45 \cdot 10^{12}\ cm^{-2}}$ within the experimental error of the optical transconductance results.

Above the AlGaN bandgap both the photovoltage and the photocurrent spectra are observed to slightly decrease with the increasing photon energy. This is due to the typical drop in the light source intensity as we move deeper into the ultraviolet. Nonetheless, no such effect is observed in the mobility curve. This is because the intensity effect is identical in the photovoltage and photocurrent and therefore cancels out in the division (Eq.3). This demonstrates the strength of the method being independent of light source intensity variations.

As evident in figure 2, the main source of noise in the mobility measurement is the photovoltage. This noise may be reduced using techniques to improve the signal to noise ratio in the Kelvin probe method [17], [18]. Another source of noise is the inherent fluctuations and arc-point shifts of the Xe lamp [19]. This may be avoided using a different light source.

V. Conclusion

In the case of the more common Hall effect method, Hall voltage is used to obtain the carrier concentration, and then the carrier concentration is used to obtain the mobility from a conductivity measurement. In the proposed method as well, we measure conductivity (channel current) but decompose it using surface photovoltage instead of the Hall voltage. The results demonstrate that the method affords a reliable alternative to Hall effect that allows to measure many transistors on a wafer to obtain statistics and wafer mapping.

References

[1] A. S. A. Fletcher and D. Nirmal, “A survey of gallium nitride HEMT for RF and high power applications,” *Superlattices Microstruct.*, vol. 109, pp. 519–537, Sep. 2017, doi: 10.1016/j.spmi.2017.05.042.

[2] R. S. Pengelly, S. M. Wood, J. W. Milligan, S. T. Sheppard, and W. L. A. Pribble, “A review of GaN on SiC high electron-mobility power transistors and MMICs,” *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 6, pp. 1764–1783, Jun. 2012, doi: 10.1109/TMTT.2012.2187535.

[3] J. A. Del Alamo, “Nanometre-scale electronics with III–V compound semiconductors,” *Nature*, vol. 479, pp. 317–323, Nov. 2011, doi: 10.1038/nature10677.

[4] S. Bajaj, O. F. Shoron, P. S. Park, S. Krishnamoorthy, F. Akyol, T.-H. Hung, S. Reza, E. M. Chumbes, J. Khurgin, and S. Rajan, “Density-dependent electron transport and precise modeling of GaN high electron mobility transistors,” *Appl. Phys. Lett.*, vol. 107, no. 15, p. 153504, Oct. 2015, doi: 10.1063/1.4933181.

[5] S. Guo, X. Gao, D. Gorka, J. W. Chung, H. Wang, T. Palacios, A. Crespo, J. K. Gillespie, K. Chabak, M. Trejo, V. Miller, M. Bellot, G. Via, M. Kossler, H. Smith, and D. Tomich, “AlInN HEMT grown on SiC by metalorganic vapor phase epitaxy for millimeter-wave applications,” *Phys. Status Solidi A*, vol. 207, no. 6, pp. 1348–1352, Jun. 2010, doi: 10.1002/pssa.200983621.

[6] J. Krupka, “Contactless methods of conductivity and sheet resistance measurement for semiconductors, conductors and superconductors,” *Meas. Sci. Technol.*, vol. 24, no. 6, pp. 062001-1–062001-13, Apr. 2013, doi: 10.1088/0957-0233/24/6/062001.

[7] Y. Turkulets and I. Shalish, “Contactless method to measure 2DEG charge density and band structure in HEMT structures,” *IEEE J. Electron Devices Soc.*, vol. 6, pp. 703–707, May 2018, doi: 10.1109/JEDS.2018.2841374.

[8] J. S. Kang, D. K. Schroder, and A. R. Alvarez, "Effective and field-effect mobilities in Si MOSFETs," *Solid-State Electron.*, vol. 32, no. 8, pp. 679–681, Aug. 1989.

[9] T. Palacios and U. K. Mishra, "AlGaN/GaN high electron mobility transistors," in *Nitride Semiconductor Devices: Principles and Simulation*, J. Piprek, Ed. Weinheim, Germany: Wiley, 2007, p. 222.

[10] M. J. Tadjer, T. J. Anderson, A. D. Koehler, C. R. Eddy, Jr., D. I. Shahin, K. D. Hobart, and F. J. Kub, "A tri-layer PECVD SiN passivation process for improved AlGaN/GaN HEMT performance," *ECS J. Solid State Sci. Technol.*, vol. 6, no. 1, pp. P58–P61, Jan. 2017, doi: 10.1149/2.0231701jss.

[11] S. P. Singh, Y. Liu, Y. J. Ngoo, L. M. Kyaw, M. K. Bera, S. B. Dolmanan, S. Tripathy, and E. F. Chor, "Influence of PECVD deposited SiN_x passivation layer thickness on $In_{0.18}Al_{0.82}N$/GaN/Si HEMT," *J. Phys. D, Appl. Phys.*, vol. 48, no. 36, p. 365104, 2015, doi: 10.1088/0022-3727/48/36/365104.

[12] C. Liu, G. Li, R. Di Pietro, J. Huang, Y.-Y. Noh, X. Liu, and T. Minari, "Device physics of contact issues for the overestimation and underestimation of carrier mobility in field-effect transistors," *Phys. Rev. Appl.*, vol. 8, no. 3, p. 034020, Sep. 2017, doi: 10.1103/PhysRevApplied.8.034020.

[13] D. K. Schroder, *Semiconductor Material and Device Characterization*, 3rd ed. New Jersey, NJ, USA: Wiley, 2006, p. 94.

[14] D. Brunner, H. Angerer, E. Bustarret, F. Freudenberg, R. Höpler, R. Dimitrov, O. Ambacher, and M. Stutzmann, "Optical constants of epitaxial AlGaN films and their temperature dependence," *J. Appl. Phys.*, vol. 82, no. 10, pp. 5090–5096, Nov. 1997, doi: 10.1063/1.366309.

[15] Y. Turkulets and I. Shalish, "Probing dynamic behavior of electric fields and band diagrams in complex semiconductor heterostructures," *J. Appl. Phys.*, vol. 123, no. 2, p. 024301, Jan. 2018, doi: 10.1063/1.5013274.

[16] F. H. Pollak, "Study of semiconductor surfaces and interfaces using electromodulation," *Surf. Interface Anal.*, vol. 31, no. 10, pp. 938–953, Oct. 2001.

[17] T. Dittrich, S. Fengler, and M. Franke, "Transient surface photovoltage measurement over 12 orders of magnitude in time," *Rev. Sci. Instrum.*, vol. 88, no. 5, p. 053904, 2017, doi: 10.1063/1.4983079.

[18] L. Kronik and Y. Shapira, "Surface photovoltage phenomena: Theory, experiment, and applications," *Surf. Sci. Rep.*, vol. 37, nos. 1–5, pp. 1–206, Dec. 1999, doi: 10.1016/S0167-5729(99)00002-3.

[19] Hamamatsu Corp. (2005). *Super-Quiet Xenon Lamp Super-Quiet Mercury-Xenon Lamp*. [Online]. Available: http://sales.hamamatsu.com/assets/pdf/catsandguides/Xe-HgXe_TLSX1044E03.pdf