Characterization and Modeling of Carrier Dynamics in Thin Films of Gallium Nitride

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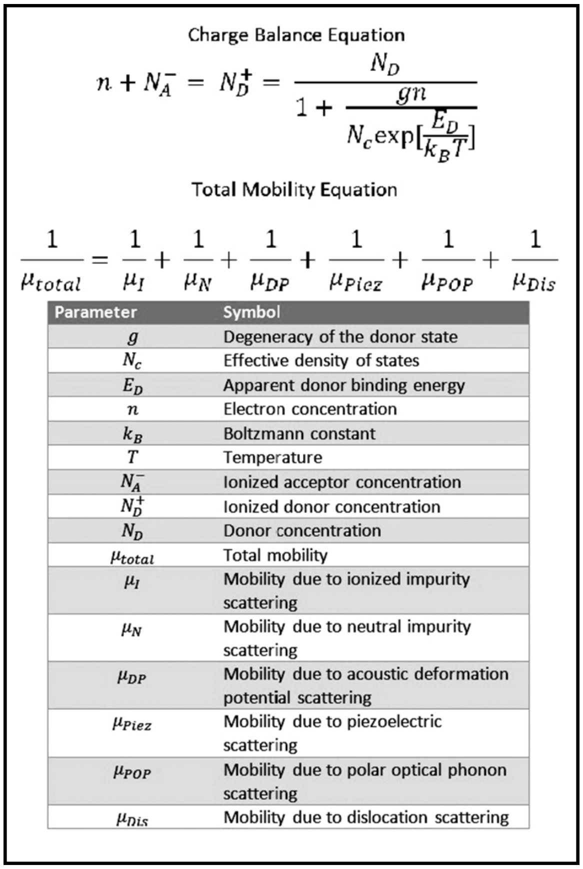
Introduction:

Gallium nitride (GaN) is used in violet laser diodes that are used to read Blu-ray disks, as well as in light emitting-diodes ranging in color from red to ultraviolet. GaN is also employed in various wireless infrastructure applications in the form of high-electron-mobility transistors (HEMTs). GaN can operate at higher powers and temperatures than many other semiconducting materials and this makes it an excellent material for use in cell phone base stations in order to improve the distance of signal transmittance. GaN transistors use less power to convert an equivalent amount of power with less energy loss than many other semiconducting materials and because of this it has the potential to improve energy retention.

An excellent way to quantify material quality is through mobility measurements. Electron scattering from impurities as well as dislocations decreases mobility. When growth conditions of the material are varied defects and thus mobility values change. By data fitting to specific equations a value for the defect concentration can be found. We created software to do this along with plotting of raw data and the mobilities due to six scattering mechanism [1].



Charge Balance Equation

$$n + N_A^- = N_D^+ = \frac{N_D}{1 + \frac{gn}{N_c \exp[\frac{E_D}{k_B T}]}}$$

Total Mobility Equation

$$\frac{1}{\mu_{total}} = \frac{1}{\mu_I} + \frac{1}{\mu_N} + \frac{1}{\mu_{DP}} + \frac{1}{\mu_{Piez}} + \frac{1}{\mu_{POP}} + \frac{1}{\mu_{Dis}}$$

Parameter	Symbol
g	Degeneracy of the donor state
N_c	Effective density of states
E_D	Apparent donor binding energy
n	Electron concentration
k_B	Boltzmann constant
T	Temperature
N_A^-	Ionized acceptor concentration
N_D^+	Ionized donor concentration
N_D	Donor concentration
μ_{total}	Total mobility
μ_I	Mobility due to ionized impurity scattering
μ_N	Mobility due to neutral impurity scattering
μ_{DP}	Mobility due to acoustic deformation potential scattering
μ_{Piez}	Mobility due to piezoelectric scattering
μ_{POP}	Mobility due to polar optical phonon scattering
μ_{Dis}	Mobility due to dislocation scattering

Figure 1: Charge balance and total mobility equations along with variable definitions [1].

Methods:

Software was created to perform data fitting of carrier concentration and mobility data taken through variable temperature Hall measurements. Carrier concentration is the density of electrons in the material, while mobility is a measurement of how well these electrons move through the material while dealing with scattering events. These data values were fit to two equations, the charge balance and total mobility equations. These equations along with the variable definitions can be referenced in Figure 1. The charge balance equation is a balance confirming that the material is electrically neutral. The total mobility equation uses Matthiessen's rule in order to consolidate mobility equations for six scattering mechanisms into the overall total mobility. Each of the six component mobility equations is based off of an individual scattering mechanism, each one having a physical basis in the material.

The program began by accepting a data set and scanning in the raw data values. These values were then plotted. An example of this plot can be referenced in Figure 2. Carrier concentration increased with temperature, while mobility increased to a peak and then decreased. Mobility took this shape because as the temperature decreased from

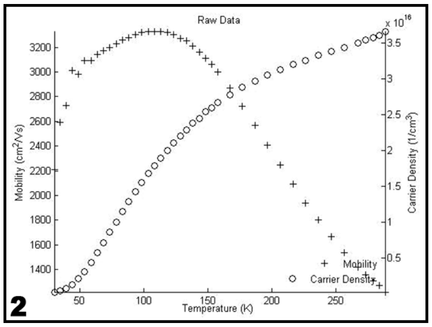


Figure 2: Raw data plot of carrier concentration and mobility data with varying temperature.

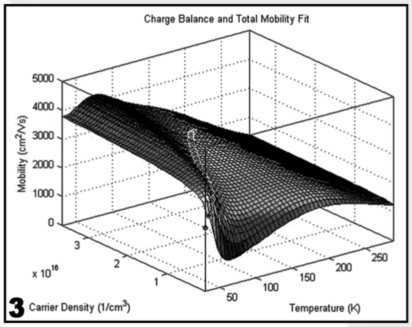


Figure 3: Fit of raw data to charge balance and total mobility equations as a surface. (See full color version on page xxxvi.)

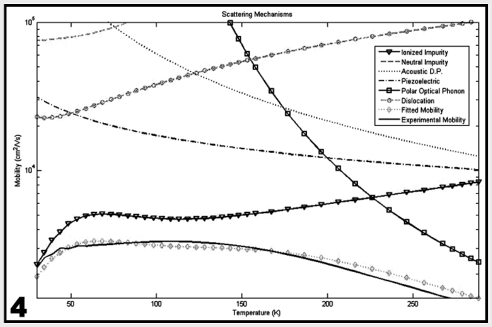


Figure 4: Mobilities due to each scattering mechanism along with total fitted and experimental mobility.

room temperature, phonons, vibrations in the lattice structure of GaN, began to lose energy and eventually freeze out. This decreased the scattering effect of polar optical phonon scattering, thus increasing the mobility. As the temperature continued to decrease, the mobility came to a peak and the effect of charge carriers themselves lost energy, and freezing out began to take over.

After the raw data values were scanned in and plotted they were fit to the charge balance and total mobility equations as a surface, which can be referenced in Figure 3. This allowed for the determination of four unknown parameter values: the acceptor concentration, N_A, which is the density of atoms in the sample that accept carriers, the donor concentration, N_D, which is the density of atoms in the material that donate carriers, the apparent donor binding energy, E_D, which is the energy required for an atom to donate a carrier, and the occupancy of traps along a dislocation, f, which is a value from 0 to 1 denoting how many traps along dislocations are occupied by a carrier. These four values can then be used in the six mobility equations for each of the scattering mechanisms as well as the total mobility equation in order to create a plot. This plot can be viewed in Figure 4.

In this plot, dominant scattering mechanisms for specific samples can be seen. Because scattering caused carriers to move more slowly, the scattering mechanism that caused the lowest mobility was the predominant scattering mechanism. In this particular sample, ionized impurity scattering was most influential up until approximately 225 K, while polar optical phonon scattering was dominant above this value.

Results and Conclusions:

Determining values for N_A, N_D, E_D, and f, along with measured mobility values, allowed for a comparison between GaN samples grown with varied conditions. N_A corresponded to approximate defect density and defect density had a direct effect on mobility and thus sample quality. As defect density increased scattering increased, therefore decreasing mobility. Materials allowing higher mobility allowed carriers to move more easily through them and thus were a better quality material.

Future Work:

In the future, we are hoping to test the effect of different power levels of the plasma source on N_A. We are expecting to see an increase in N_A with an increase in power level as increasing the power level supplies the sample with more energy in order to create more ionized atoms and thus acceptors. We also want to test different flow rates of the plasma source and expect to see a similar correlation between it and N_A.

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References:

[1] Kyle, Erin C.H., Stephen W. Kaun, Peter G. Burke, Feng Wu, Yuh-Renn Wu, and James S. Speck. "High-electron-mobility GaN Grown on Free-standing GaN Templates by Ammonia-based Molecular Beam Epitaxy." Journal of Applied Physics 115.193702 (2014).