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# Energy relaxation of hot electrons by LO phonon emission in AlGaN/AlN/GaN heterostructure with *in situ* $Si_3N_4$ passivation

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ABSTRACT

In this study, energy relaxation mechanisms of electrons in AlGaN/AlN/GaN High Electron Mobility Transistor (HEMT) structures with and without *in situ* $Si_3N_4$ passivation were investigated. Although the physical parameters of the samples were all different, the electron-temperature dependent power loss values were found to be identical. The study also sought to fit the current theoretical power loss in the LO-phonon regime to the experimental power-loss per carrier results. The calculated power loss offered a reasonably fit to the experimental data in the electron temperature range between 75 and 250 K.



## 1. Introduction

GaN-based High Electron Mobility Transistors (HEMT) have outstanding features such as very high carrier densities, high saturation velocities and high breakdown fields. GaN-based HEMTs are therefore widely used in millimeter-wave power applications such as cell phones, radar installations and satellites [1]. In the development of this very successful technology, the knowledge basis for the application of wurtzite nitride heterostructures to advanced optical and electronic devices requires an understanding of the electronic properties of their surfaces and interfaces and also their interplay with the polarization charges at the heterojunctions, which characterize the wurtzite III-N heterostructures in comparison with the classical zincblende III–V ones. A number of problems still hamper further development, most notably a lack of understanding of the origin and ensuing lack of control of the two-dimensional electron gas (2DEG) in undoped AlGaN/GaN heterostructures and the phenomenon of current collapse in high-frequency transistor devices, which might result in issues related to noise, power loss and reliability. Current collapse is the biggest obstacle to obtaining reproducible power performance and it continues to represent an unsolved problem. Among several mechanisms, the most widely accepted one is that the 2DEG originates from donor states on the AlGaN surface, moreover, surface states are responsible for current degradation in transistor devices. Much attention has been focused on the reduction of parasitic surface states using different passivation dielectrics and one of the most promising of these is the $Si_3N_4$ grown *in situ* by molecular beam epitaxy (MBE) without exposing the semiconductor surface to the air environment [2–5]. However, in spite of it demonstrating encouraging effectiveness of *in situ* $Si_3N_4$ passivation, its mechanism is still not fully understood.

Non-electrical or optical interactions can produce unstable free carriers in semiconductors. The extra energy gained by the electron or hole is consumed by the interaction with the optical and acoustic lattice vibrations of phonons. Comparing experimental results with theoretical studies should provide indirect information about a carrier's energy distribution function [6].

An in-depth understanding of the fundamental optoelectronic properties is yet to be established for the design and development of functional devices. The determination of the temperature of electrons under electric-field heating conditions in the steady state

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provides useful information about the electron-phonon interactions involved in the energy relaxation process (for a review, see Ref. [7]). Furthermore, investigations of electron-phonon scattering processes determine high-field transport phenomena in semiconductors and thus form the basis of many ultrafast electronic and optoelectronic devices. The field of hot carriers in semiconductors thus provides a link between fundamental semiconductor physics and high-speed devices. Despite the fact that the energy relaxation time is a scientifically technological and fundamental important parameter for designing optoelectronic devices, the energy relaxation time is not yet well-known.

There are four experimental techniques that have been widely and successfully employed in the investigation of electron energy relaxation. First, in heavily modulation-doped structures where a highly degenerate electron gas exists, the amplitude variation of quantum oscillations, such as the Shubnikov-de Haas (SdH) effect, with the applied field and lattice temperature can be used in the determination of the electron temperature-power loss characteristics [8]. Second, in a material in which the momentum relaxation is dominated by ionized impurity, remote impurity, interface roughness or optical phonon scattering [9], electron temperatures as a function of the applied electric field can be determined by a simple comparison of the electric field-dependent and lattice temperature-dependent mobility curves. Third, with the noise technique, the electron temperature can be estimated by measuring the electromagnetic radiation resulting from the fluctuations in the electron velocities under the high electric field [10]. Fourth, with the pump probe Raman spectroscopy technique, the energy relaxation time can be directly determined from the decay of the anti-Stokes line intensity [11].

Of the four techniques, the second one, the mobility comparison technique is preferred to obtain the temperature of non-thermal equilibrium electrons just because of the very small size of the samples and the low electroluminescence nature of the samples [12–23]. This method can be applied to non-degenerate or less degenerated two-dimensional electron gas systems [12,17]. This method was also successfully used for GaN-based semiconductors [18,19,23]. It includes both an electric field ($F$) dependent mobility ($\mu_F$) at constant lowest lattice temperature ($T_{L0}$) measurements and a lattice temperature ($T_L$) dependent mobility ($\mu_T$) at constant lowest electric field ($F_0$) measurements. The results of both measurements are normalized by the joint mobility value determined at the lowest electric field and temperature. The electric field-dependent electron temperature is obtained by using the normalized results.

Bauer and Kahlert [24] investigated the lattice temperature and electric-field dependence of the low-field electron mobility in GaAs. They found that the changes in electron mobility with both lattice temperature and electric field are almost the same. According to this hypothesis, the following equation can be derived:

$$\left[\frac{\mu_{(T_L)}}{\mu_{(T_{L0})}}\right]_{F=F_0} = \left[\frac{\mu_{(F)}}{\mu_{(F_0)}}\right]_{T_L=T_{L0}} \quad (1)$$

In order to use mobility comparison method, three conditions must be fulfilled [19,23]. First, this approximation is applicable when the carrier density of the system is not increasing with the increasing applied electric field [23]. Therefore, applied electric field only results an increasing in the energy of the carriers, not the number of the carriers. This condition can be accepted to be fulfilled in our study because of temperature independent behavior of 2D carrier density. However, due to thermally activated parasitic bulk carriers at high temperatures, carrier density may show an insignificant change. Second, it is accepted that electron–electron scattering, which is the dominant mechanism at high temperature (or high electric field), thermalizes the hot electrons among themselves. Third, the energy relaxation of non-equilibrium electrons is due to longitudinal optical phonon emission via polar or non-polar interaction.

In this current study, the power loss of hot electrons was determined as a function of the applied electric field and electron temperature by using the mobility comparison method in AlGaN/AlN/GaN heterostructure samples with different doping and layer structures which were grown by MBE with or without growth *in situ* of an $Si_3N_4$ passivation layer. The results are discussed in the framework of the current theoretical models concerning carrier energy loss rates in GaN-based and InN-based semiconductors.

## 2. Experimental method

AlGaN/AlN/GaN heterostructures with and without *in situ* $Si_3N_4$ passivation were grown by MBE on (001)-oriented 400-μm-thick sapphire substrates in a Riber 32 machine (*see* Table 1 for the sample structures). The samples are fabricated in Hall bar shapes and the details of the Hall-bar shaped sample have been reported elsewhere [25]. The electric field ($F$) dependent mobility ($\mu_F$) at constant lowest lattice temperature ($T_{L0}$) measurements and lattice temperature ($T_L$) dependent mobility ($\mu_T$) at constant lowest electric field ($F_0$) measurements were made for each Hall-bar geometry shaped sample in the temperature range from 75 to 270 K in a cryogen-free superconducting magnet system (Cryogenics Ltd) using an orthodox dc technique.

The high-speed current–voltage (I–V) characteristics were measured using simple-bar-shaped samples of lengths $l = 4$ μm and $w = 1$ μm. In the pulsed I–V measurements, voltage pulses of 20 ns duration with a duty cycle of 0.005% were applied along the length of the sample up to a maximum electric field of $F = 500$ kV/cm with Avtech AVIR-3-B high voltage pulser in a home-made LN2-cooled sample holder. With very short and symmetrical cabling for the sample holder, it is possible to maintain very good impedance matching. Therefore, shape of the pulses did not affected much up to these high electric field values. The applied voltage and current through the sample were measured using a 300 MHz real time oscilloscope at 77 K.

## 3. Results and discussions

Fig. 1 shows the conduction band of the investigated samples with $Si_3N_4$ passivation. Samples without $Si_3N_4$ passivation, #952 and #955 show similar band structure behaviors with the without $Si_3N_4$ layer #953 and #954, respectively. Therefore, they are not drawn in the figure. Bending in the barrier layer of n-AlGaN/AlN/GaN structure is due to doping in the barrier layer. Structures with AlN interlayers show deeper pseudotriangular quantum well depths which results higher carrier densities and narrow electron probability functions [26]. Both results are known to change the temperature dependent mobility limiting behavior [27].

Fig. 2 shows a typical example of the temperature dependent and electric-field dependent mobility. The data clearly show that the decrease in the mobility with increasing lattice temperature or electric-field results in decreasing scattering length with various scattering mechanisms. Even the characteristic of the mobility curve has the same trend for the all investigated samples, the mobility values are different due to temperature independent carrier scattering mechanisms *i.e.* interface roughness scattering, remote impurity scattering, alloy disorder scattering [28,29] In our field-dependent mobility calculations, experiments are done with electric-fields up to about 500 kV/cm successfully without losing an important amount of the shape of the investigated voltage pulses.