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Mechanism of hot electron electroluminescence in GaN-based transistors

Tommaso Brazzini[1,4], Huarui Sun[1], Francesco Sarti[2], James W Pomeroy[1], Chris Hodges[1,3], Massimo Gurioli[2], Anna Vinattieri[2], Michael J Uren[1] and Martin Kuball[1]

[1] Center for Device Thermography and Reliability, H. H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, UK
[2] Dipartimento di Fisica e Astronomia and LENS, Università di Firenze, Via Sansone 1, I-50019 Firenze, Italy

E-mail: tommaso.brazzini@bristol.ac.uk

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Abstract

The nature of hot electron electroluminescence (EL) in AlGaN/GaN high electron mobility transistors is studied and attributed to Bremsstrahlung. The spectral distribution has been corrected, for the first time, for interference effects due to the multilayered device structure, and this was shown to be crucial for the correct interpretation of the data, avoiding artefacts in the spectrum and misinterpretation of the results. An analytical expression for the spectral distribution of emitted light is derived assuming Bremsstrahlung as the only origin and compared to the simplified exponential model for the high energy tail commonly used for electron temperature extraction: the electron temperature obtained results about 20% lower compared to the approximated exponential model. Comparison of EL intensity for devices from different wafers illustrated the dependence of EL intensity on the material quality. The polarization of electroluminescence also confirms Bremsstrahlung as the dominant origin of the light emitted, ruling out other possible main mechanisms.

Keywords: electroluminescence, high electron mobility transistor, AlGaN/GaN, electron temperature, Bremsstrahlung, hot electrons

(Some figures may appear in colour only in the online journal)

1. Introduction

Electroluminescence (EL) from electronic devices has been the focus of research to study electric field distribution [1, 2], carrier distribution [3], and device reliability [4–10], in particular recently on GaN based high electron mobility transistors (HEMTs). EL was observed in Si, GaAs, and GaN p–n junctions, Gunn diodes and transistors [11–20], when operated at high electric fields. The light spectral distribution and physical mechanism have been shown to be dependent on the material type, however some common characteristics were found. Often band-edge recombination, i.e. an electron and a hole recombining, can be seen for example after impact ionization in GaAs devices. The presence of a Bremsstrahlung mechanism (braking radiation) in high field regions of the device [11], has been suggested to be the origin for additional light emission at energies below the band gap for Si and GaAs [3, 14, 21–25]. However, for GaN based devices the nature of EL where no band gap recombination has been observed [26]

[3] Present address: School of Physics and Astronomy, Cardiff University, Queen's Buildings, The Parade, Cardiff CF24 3AA, UK.
[4] Author to whom any correspondence should be addressed.

and only sub-bandgap emission is visible, has been surprisingly hotly debated, and in addition to Bremsstrahlung, attributed to many different origins. The presence of peaks and ripples in the EL spectrum has been associated with recombination via defect states [6, 28], for example yellow luminescence centers [6, 29], or with radiative intervalley transitions [27]. Despite this lack of an unambiguous explanation of the emission mechanism, EL of GaN-based transistor has been used as a reliability indicator for hot electron concentrations [5, 6, 30]. The degradation rate showed a strong dependence on the number of hot electrons in the channel which was assumed to be proportional to the EL intensity [7]. It has been commonly accepted that the high energy part of the EL emission can be used to extract the electron temperature (T_{el}) [3, 5, 26, 30], with the high photon energy tail of the emission spectrum assumed to be related to the hot electron energy distribution in the form:

$$I_{EL} \sim \exp(-E_{photon}/[k_B T_{el}]), \quad (1)$$

where I_{EL} is the EL intensity, E_{photon} the measured photon energy and k_B the Boltzmann constant. This expression, however, has very limited justification. In this letter, the spectrum of EL emission is studied in a wider photon energy range (from 0.8 to 2.8 eV) than previously studied [6, 8, 9, 18, 26, 27]; interference effects due to multiple reflections in the device structure, often neglected or erroneously attributed to defect states, are taken into account in the present work. In addition, a comparison of EL intensity for devices from different wafers with the same layout and similar structures and the measurements of the bias dependent polarization of the emitted light clearly show that light intensity is related to the density of Coulomb scattering centres, both observations being consistent with Bremsstrahlung radiation. The measured EL from high field regions in an AlGaN/GaN HEMT is shown to be entirely consistent with the fit to a Bremsstrahlung radiation model.

2. Experimental details

The devices studied here were 2×50 μm AlGaN/GaN HEMTs grown by metal-organic chemical vapor deposition (MOCVD) on SiC substrates. The heterostructure consisted of a 1.9 μm Fe-doped GaN buffer layer and a 25 nm $Al_{0.25}Ga_{0.75}N$ barrier layer. Standard Ti/Al/Ti/Au Ohmic contacts were used for the source and drain electrodes, and Ni/Au Schottky contact for the gate electrode. The AlGaN/GaN HEMTs were passivated with a SiN_x layer and isolated by mesa etching. 'I-shaped' gated devices were considered for this study to avoid light shadowing in field-plated or 'T-gated' transistors. Three other devices with the same layout and with similar heterostructures were also studied and the EL intensity compared (discussed later). For spectral measurements, two different optical systems were used in order to cover a broad spectral range. For low energy EL spectra (0.8–1.3 eV), the device was mounted on a TO-8 package. The light emitted from the device was collected through a system of lenses and sent to the spectrometer (SP-2300 Acton, 300 l mm^{-1} grating)

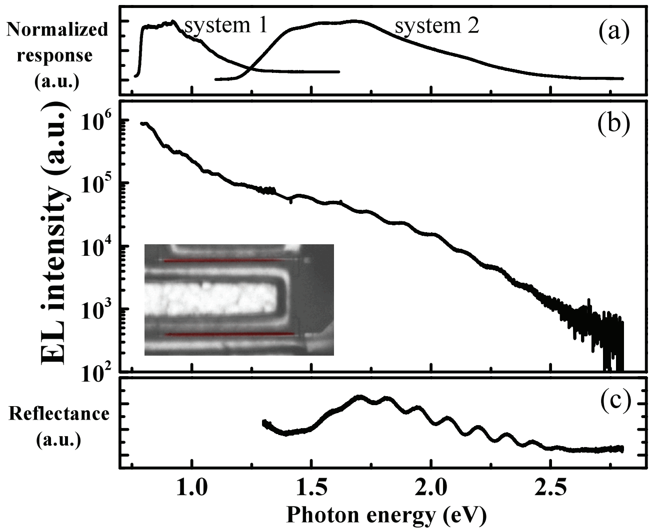

Figure 1. (a) Spectral response curves of the two optical systems used to obtain the wideband EL emission spectrum from the AlGaN/GaN HEMTs; (b) spectrum of the EL emission for the AlGaN/GaN device under study under $V_{DS} = 20$ V and $V_{GS} = 0$ V bias condition, corrected with the optical response curves of the detection systems of (a), but not corrected for interference effects of the sample thick layers. Inset shows false color image of the EL emission from the device. (c) Reflectance spectrum of the sample layers in the area of EL emission, measured with system 2.

and then to the liquid nitrogen-cooled InGaAs detector (OMA V, Princeton Instruments) (system 1). For the high energy range (1.3–2.8 eV) the device was mounted on a microscope stage and the emitted light was collected with a 50×, 0.6 NA objective and a Renishaw InVia spectrometer (1200 l mm^{-1} grating) with a silicon CCD (system 2). The value obtained by the measurements using both systems is the light intensity that can be expressed as the number of photons multiplied by the energy of each photon (see below). The spectral responses for both systems were determined using calibrated lamps and are shown in figure 1(a). In both cases, thermal paste was used to place the device in contact with metal heat sinks to ensure good heat dissipation; the peak channel lattice temperature was measured with Raman thermography and estimated to be below 60 °C for the bias conditions used, and hence the effect of lattice temperature on the EL emission is negligible [31]. EL microscopy was used for light polarization measurements: Images of the device EL emission under DC bias conditions were recorded using a polarizer and a high-resolution CCD camera.

3. Results and discussions

The spectrum of EL emission in the energy range (0.8–2.8) eV is displayed in figure 1(b). The light intensity monotonically decreases with increasing photon energy and no clear peaks are apparent. The lack of a distinct peak suggests that the origin of EL is not related to an intervalley transfer [20, 27] or to high conduction band band-to-band optical transitions, or to a defect-related recombination [6, 28], as has been suggested by some in the literature. The reflectance spectrum of the device was measured under white light illumination with

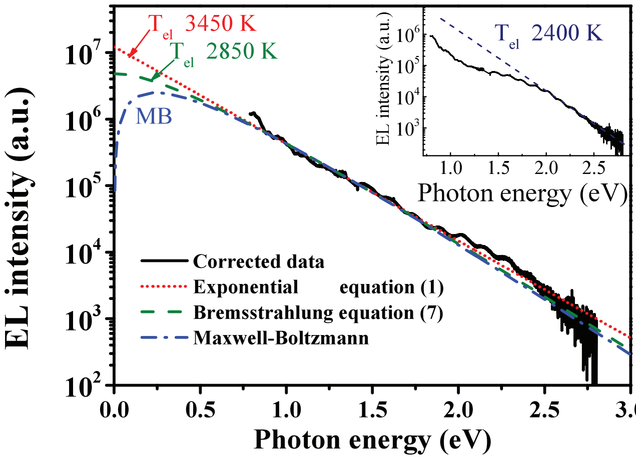

Figure 2. Measured EL spectrum of AlGaN/GaN HEMT at $V_{DS} = 20\,V$ and $V_{GS} = 0\,V$ bias conditions after correction using a Fabry–Perot etalon transmittance for the SiN_x passivation (black), fitted using the simplified exponential in equation (1) (red dotted curve) and the full analytical expression of equation (7) (green dashed curve). The Maxwell–Boltzmann distribution (MB) is also shown as a comparison (blue dash-dotted curve). In the inset the fitting of the experimental data with equation (1), not corrected for interference fringes, in the higher energy tail of the spectrum.

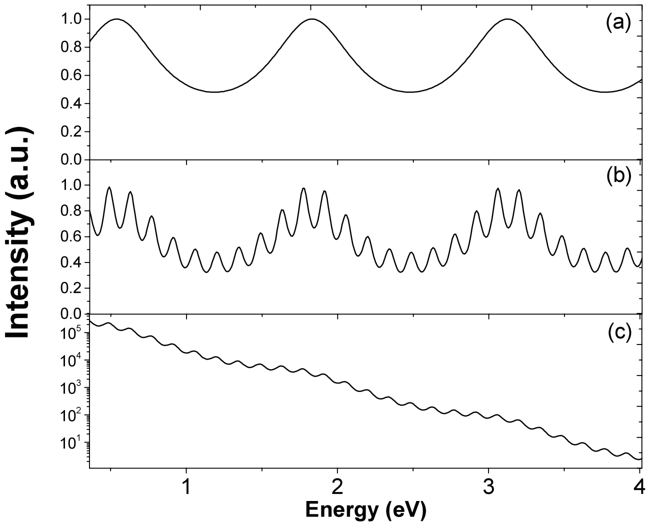

Figure 3. Simulations of the effect of the interference fringes on the final EL spectral response: (a) transmission spectra due to the SiN_x alone. (b) Transmission spectra due to both SiN_x passivation layer and the GaN thick buffer layer. (c) Spectrum, reported in Log scale, obtained as the superposition of the interferences due to GaN and SiN_x with a simple exponential response due to Bremsstrahlung (as discussed in the text).

optical system 2 (figure 1(c)) to be able to observe interference fringes related to any layer in the structure (SiN_x passivation, AlGaN/GaN, AlN nucleation layer, etc). Using the refractive indices of each layer [32], the short period oscillations were found to be associated with the GaN layer thickness (~2 m) and the long period oscillations can be ascribed to the SiN_x passivation layer (~200 nm); in that spectral range only two local minima (at around 1.4 eV and 2.8 eV) and one local maximum (at around 1.7 eV) of the latter interference fringes are visible. These features also appear in the measured EL spectrum in figure 1(b), which can easily lead to misinterpretations of the data, if assigned to optical transitions [6, 27] or when determining hot electron temperature from the spectrum. The long period oscillation apparent in figure 1(b) was corrected, with the result shown in figure 2, using a typical Fabry–Perot etalon transmittance formula: $\left(\frac{1}{1+F(\sin^2(\omega E+\varphi))}\right)$ with F being the finesse of the etalon, ω the oscillation frequency and φ the phase of the oscillation. The short frequency interference fringes due to the GaN layer were not corrected, as they do not interfere severely with the determination of the electron temperature and are not easy to correct for in the spectra. If correction for interference effects due to the SiN_x passivation is not carried out, as can be seen in the inset of figure 2, the electron temperature extracted using only the high energy tail with the exponential form is underestimated by approximately 1000 K (30% deviation).

To better understand how the multilayer structure influences the EL response we simulated separately the contributions of each layer and then superimposed them. The results are shown in figure 3.

To gain insight into the emission characteristics expected for a Bremsstrahlung related mechanism, we here derive an analytical expression for the spectral distribution of emitted photons. We consider the emission of light as a mechanism for hot electrons to relax to lower energy states, as an alternative to the emission of longitudinal optical (LO) phonons which decay to longitudinal acoustic (LA) phonons and heat the sample [33]. We assume the presence of imperfections such as defects, dopants or alloy disorder at the AlGaN/GaN interface that will suffer inelastic recoil during electron collisions and photon emission, overall with momentum and energy conservation. Electrons decelerated by charged scattering centers will lose energy E at the rate classically given by the Larmor's formula for a single scatterer in vacuum (Bremsstrahlung) [23, 24]:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{2e^2a^2}{3c^3} \tag{2}$$

where e is the electron charge, a the acceleration, and c the speed of light. By using equation (2) we assume that the properties of the medium for light propagation will not change significantly with photon energy. The probability $q(\nu, E)$ of an electron with initial energy E to emit a photon of energy in the range $[h\nu, h(\nu + \mathrm{d}\nu)]$ after a collision, will follow the expression given by [11, 14, 23]:

$$q(\nu, E)h\nu\mathrm{d}\nu = \frac{32\pi^2}{\sqrt{27}}\frac{e^6}{c^3E}\mathrm{d}\nu. \tag{3}$$

To obtain the number of photons created, $N_p(h\nu)$, in the interval $\mathrm{d}\nu$ due to electrons in the energy range $\mathrm{d}E$, one needs to consider the electron distribution function $N(E)$ the density of states $D(E)$ and the velocity of the electrons $v(E)$ expressed in terms of the energy E:

$$N_p(h\nu)\mathrm{d}\nu\mathrm{d}E = q(\nu, E)N(E)v(E)D(E)\mathrm{d}\nu\mathrm{d}E \tag{4}$$

where the total number of electron collisions in the interval $\mathrm{d}E$ for a definite density of scatterers N_{sc} is $C(E) = N_{sc}N(E)D(E)v(E)$ $\mathrm{d}E$. For $D(E)$ the 3D case is assumed; to obtain $N(E)$ out of equilibrium (i.e. with an external perturbation due to the electric field) the following form has to be considered:

$$N(E) = N_{\mathrm{pert}}(E) - N_{\mathrm{eq}}(E) \tag{5}$$

where $N_{\mathrm{pert}}(E)$ and $N_{\mathrm{eq}}(E)$ are the electron distributions with external perturbation and at equilibrium, respectively. The perturbed distribution is characterized by an electron temperature (T_{el}) which at equilibrium (N_{eq}) reduces to the lattice temperature (T_{latt}) while the equilibrium distribution is negligible compared to the perturbed one. $N(E)$ can then be approximated with the Maxwell–Boltzmann distribution with a specific electron temperature (T_{el}). The intensity of EL emission can therefore be written as $I(h\nu)\mathrm{d}\nu = N_{\mathrm{p}}(h\nu)h\nu\mathrm{d}\nu$; this can be obtained by integrating equation (3) over the energy range that electrons can reach under the electric field in the conduction band, i.e. from $h\nu$ up to infinity, ignoring impact ionization [26, 34] and intervalley transfer [20] for the maximum value of integration.

$$I(h\nu)\mathrm{d}\nu = A\left(\int_{h\nu}^{\infty}\sqrt{\left(\frac{1}{k_{\mathrm{B}}T_{\mathrm{el}}}\right)^{3}}\,E\mathrm{e}^{-\left(\frac{E}{k_{\mathrm{B}}T_{\mathrm{el}}}\right)}\mathrm{d}E\right)\mathrm{d}\nu \tag{6}$$

Here A is a proportionality constant and k_{B} the Boltzmann constant. After the integration we obtain the spectral distribution of EL intensity as:

$$I(h\nu)\mathrm{d}\nu = A\sqrt{k_{\mathrm{B}}T_{\mathrm{el}}}\left[\frac{h\nu}{k_{\mathrm{B}}T_{\mathrm{el}}}+1\right]\mathrm{e}^{-h\nu/k_{\mathrm{B}}T_{\mathrm{el}}}\mathrm{d}\nu \tag{7}$$

where the proportionality constant $A = 17.4\frac{q^{6}1^{/2}\pi^{1/2}}{c^{3}\hbar^{3}}m^{*3/2}N_{\mathrm{SC}}$.

The extraction of the equations did not take into account the 2D nature of the 2DEG for simiplicity, although it can be extended to a 2DEG.

As is apparent in figure 2, equation (7) (dashed green curve) derived strictly from Bremsstrahlung, gives a spectral behavior similar to the often assumed simple exponential tail using equation (1) (red dotted line) at high energy, while at low energy the deviation becomes more significant, but only in the low photon energy range which is very challenging to access experimentally. There are some differences in the spectral distribution between the full expression of equation (7) and the phenomenological Maxwell–Boltzmann distribution (MB), mostly related to the absence of a peak at low energies for the extracted expression in equation (7). The derived equation allows a more accurate determination of the hot-electron temperature than the simplified exponential form observing a reduction of the electron temperature extracted of about 20%, and it is of crucial importance for understanding the hot-electron relaxation and how the electron distribution affects the spectral distribution of light emission. No yellow luminescence or defect-related peak is observed once the correction is carried out and the spectral distribution of EL varies exponentially in the range observed. No other mechanisms proposed in the literature other than Bremsstrahlung give an exponential behavior, which rules out any other origin of the observed emission.

A key enabler for Bremsstrahlung to occur is the presence of scattering centers that will de-accelerate the electrons. To further confirm the hypothesis that the EL in AlGaN/GaN HEMT is predominantly related to Bremsstrahlung, the EL intensity was measured for three 1×100 μm AlGaN/GaN devices on SiC substrates with exactly the same layout, processed on different wafers and having similar sheet carrier density (~5×10^{12} cm^{-2}) and similar mobility measured in the low field regime (~2000 cm^{2} V^{-1} s^{-1}). The results are shown in figure 4. As the EL intensity is proportional to the current density, it was normalized using the measured drain current for this comparison [6]. The electric field distribution in the devices will be similar since they have the same device layout and structure.

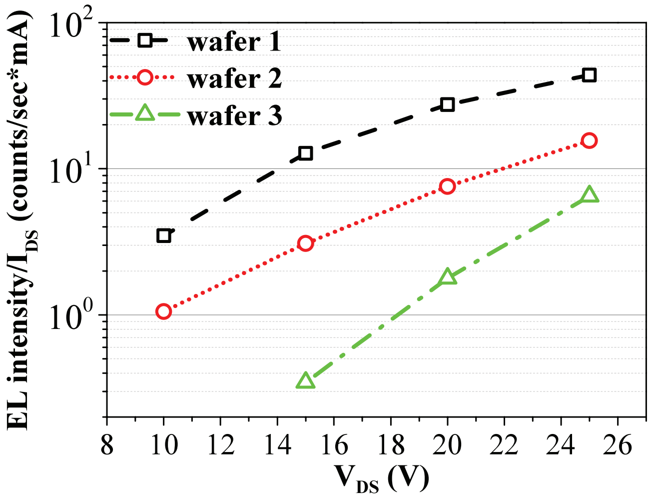

Figure 4. EL intensity scaled by the drain current (I_{DS}) as function of source drain bias, for devices with identical layout on different wafers.

Clearly the EL emission intensity has a significant variation depending on the wafer. The reason of such a large wafer-to-wafer variation is not clear. One possibility is the differences in defect density in the AlGaN barrier, at the AlGaN/GaN interface and also in the GaN buffer, since electrons can penetrate deep at high enough electric fields. We believe that a small proportion of defects present in the wafers are possibly responsible for the big variations observed in the EL intensity, and there is no easy way to monitor them. However it is clear how this effect cannot be due to an intrinsic mechanism since for wafers with similar surface properties (mobility and electron density) a similar EL intensity would be expected. This is again consistent with Bremsstrahlung being the dominant mechanism in AlGaN/GaN HEMTs for EL emission, as point defects, charged dislocations, and interface roughness scattering are responsible for momentum conservation during the light generation.

Taking into account that the 2DEG is a confined state, the scattering probability should be lower than in the 3D case. However when the drain bias increases, the vertical component of the electric field will induce the electron to flow deeper into the buffer layer and escaping from the 2D quantum well. So up to a certain extent we can state that charged defects that can induce the EL can be related to the buffer, but it is still a challenging task to quantify the density of defects responsible for the Bremsstrahlung.

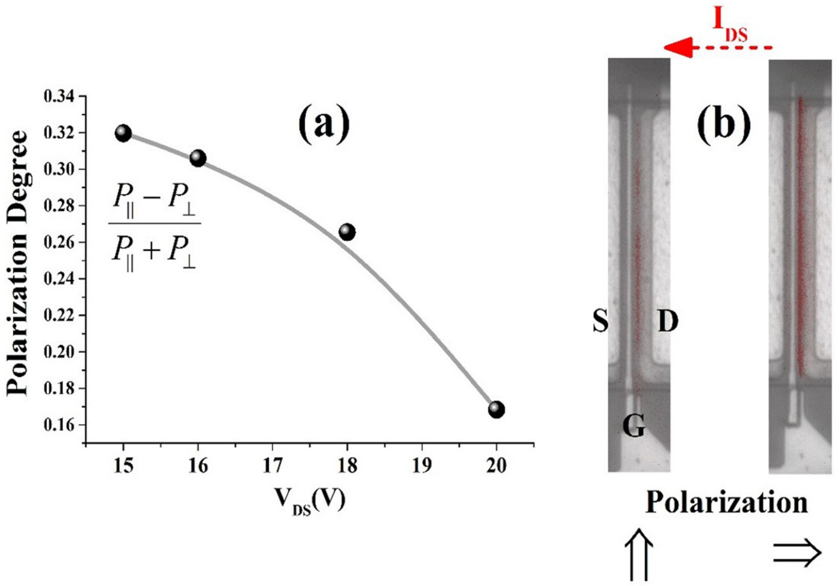

Figure 5. (a) Polarization degree $(P_{\parallel} - P_{\perp})/(P_{\parallel} + P_{\perp})$ of the light emitted from the device versus V_{DS} under conditions of ON-STATE ($V_{GS} = 0$). The line is a guide to the eye. (b) False color EL image of the device under study for polarizations perpendicular and parallel to the direction of current flow, recorded at $V_{DS} = 15$ V with the location of the source (S), drain (D), and gate (G) indicated.

The Bremsstrahlung theory also predicts that light polarization should be given by the following expression for vector components [23, 35]:

$$\overrightarrow{P_{EL}} = \vec{n} \times (\vec{n} \times \vec{a}), \tag{8}$$

where $\vec{n}$ is the normal to the device surface, and $\vec{a}$ is the direction of electron acceleration under electric field biasing. Whenever electron scattering results in the forward direction (parallel to the current) the light polarization is also parallel to the current [23, 36]. Previous observations show that light is polarized along the current flow direction in AlGaN/GaN [37, 38] and AlGaAs/GaAs [39] devices. However the dependence of the polarization behavior on the applied electric field (V_{DS}) has not been studied so far in GaN-based devices. The light polarization was measured parallel ($P_{\parallel}$) and perpendicular ($P_{\perp}$) to the current by means of EL microscopy, and the polarization degree, defined as $P_D = \left(\frac{P_{\parallel} - P_{\perp}}{P_{\parallel} + P_{\perp}}\right)$, was calculated, as shown in figure 5. Clearly apparent is the presence of polarized light, consistent with earlier reports, which confirms again the presence of the Bremsstrahlung mechanism. However, the magnitude of polarization degree depends on the bias voltage applied (V_{DS}), i.e. it is more complicated than earlier reports seem to suggest. The highest polarization degree is observed at low V_{DS}, and decreases with an increasing V_{DS}. On the other hand, no change in the spectral shape of the emission was observed (i.e. no features in the spectrum) with increasing electric field (V_{DS}). Hence, no change in the emission mechanism should occur. A plausible explanation is that at low electric fields, electrons primarily travel in the two dimensional gas (2DEG) channel, or very close to it, and the current is substantially parallel to the sample surface. Due to the increase in V_{DS}, electrons will be pushed deeper into the buffer layer [40] and the scattering direction will change. This effect would reduce the fraction of the EL polarized parallel to the current. The overall result is that from the top it is not possible to detect a preferential polarized direction when the drain bias is high. At the same time, optical effects such as multilayer transmissions and reflections of the EL emitted in the sample structure as well as reflections from the surrounding metal contacts will likely affect the polarization state of the light escaping from the device.

4. Conclusions

In conclusion, EL emission from GaN HEMTs was studied and unambiguously assigned to Bremsstrahlung. The importance of separating interference effects and the actual EL emission has been highlighted for the first time and shown to be crucial for the correct analysis of EL spectra and avoid artefacts in the interpretation of the results. An analytical expression was derived, based on Bremsstrahlung theory, to fit the experimental EL data and compared to the approximated model based on high energy exponential tail. A reduction of about 20% in the electron temperature extracted with the new expression compared with the simple exponential behavior is reported. Measurements of EL intensity using devices from different wafers and polarization measurements further confirm that scattering of electrons with defects in the material is the origin of the EL, excluding the previously suggested explanation that EL emission in a GaN-based transistor is related to interband/intervalley optical transitions [27] or defect assisted recombination [6]. The following points can be summarized to support the Bremsstrahlung mechanism as the origin of EL emission:

- A **feature-less broadband continuum spectrum** is typical for Bremsstrahlung-related emission, while for example, intervalley scattering is supposed to result in a spectrum featured with peaks or 'bumps' generally related to discrete transitions, which is not the case in the present study.

- For similar surface properties (carrier density and electron mobility of the three wafers) we observe **big variations in EL emission** possibly to correlate with the properties (defects, dislocations etc…) of the whole structure, in particular the buffer layer.
- **Polarization** of the light emitted, which is typical of Bremssthralung mechanism. In case of other type of emission, such as intervalley transitions, no polarization is expected.

Acknowledgments

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