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Avalanche Breakdown Luminescence of InGaN/AlGaN/GaN Heterostructures

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Abstract

Luminescence spectra of InGaN/AlGaN/GaN p-n-heterostructures were studied at reverse bias sufficient for impact ionization. There is a high electric field in the active InGaN-layer, and the tunnel component of the current dominates at the low reverse bias. Avalanche breakdown begins at $|V_{th}|>$ 8◊10 V, i.e. ≈3 E_g/e. Radiation spectra have a short wavelength edge 3.40 eV, and maxima in the range 2.60◊2.80 eV corresponding to the injection spectra. Mechanisms of the hot plasma recombination in p-n-heterojunctions are discussed.

1. Introduction

Injection luminescence spectra of superbright blue and green light-emitting diodes (LEDs) based on InGaN/AlGaN/GaN heterostructures were studied in [1] [2] [3] [4] [5]. It was interesting to study the breakdown luminescence in the same structures hoping to receive some additional information on the parameters which influence on the properties of effective LEDs.

Avalanche breakdown luminescence in GaN was studied previously in cases of i-n- and MIS - diodes [6] [7] [8] [9]. It was shown that at reverse bias, electrons are tunneling from metal to the n-side of the junction and at sufficiently high voltage cause impact ionization and avalanche breakdown.

There is a high electric field in the active layer of the blue InGaN/AlGaN/GaN LEDs as it was concluded from the spectral and capacitance measurements [3] [4] [5]. The high doping of the p-side and a thin active layer distinguish these LEDs from the previous [6] [7] [8] [9] [10] ones. In this paper we describe breakdown luminescence spectra of blue LEDs and analyze electrical and luminescence properties of InGaN/AlGaN/GaN structures at reverse bias.

2. Experimental results

We have studied the LEDs based on the InGaN/AlGaN/GaN structures with a thin layer - quantum well InGaN - described in [1] [2]. Blue LEDs with known parameters of the injection luminescence spectra [2] [3] [4] were chosen for measurements. Reverse current-voltage and capacitance-voltage curves of a blue diode (N 3) are shown in Figure 1 and Figure 2.

The main part of the curves at |V|< 10 V can be approximated by two exponents:

$$J \sim \exp(e|V|/E_J), \qquad (1)$$

with a parameter E_J = 0.86◊0.90 eV changing near |V| = 5◊6 V. The change in the slopes of derivatives dV/d(lnJ) is shown in Figure 1. The reverse current-voltage characteristics of the green LEDs differed from the blue ones (see Figure 3), according to lower electric fields in the structures [2] [3] [4]. The values of E_J were almost independent on the temperature (T = 80◊300 K). This behavior is attributed to a tunnel component of the current. It is to be noted that some changes in the J(V) characteristics near |V| = 5◊6 V were seen by other authors [10] [11] but they did not pay attention to these facts.

The impact ionization begins at higher voltages |V|> 8◊10 V as can be concluded from a minimum of C(V) curves (a maximum of the curves $1/C^2 = f(V)$ is seen in Figure 1. The luminescence could be detected at a threshold of about $V_{th} \approx -11$ V. We have measured the luminescence spectra at the currents |J|< 5 mA which were not destructive for the blue diodes. The luminescence - radiative recombination - indicated a creation of the minority carriers as a result of the impact ionization. The luminescence was visually non homogeneous because of microplasma mechanism of breakdown current.

The breakdown luminescence spectra for three LEDs are shown in Figure 4. The injection luminescence spectra are also shown. The intensity of the breakdown luminescence is 6-7 orders of magnitude lower than of the injection ones, as indicated on the ordinate axes.

The broad band of luminescence is seen in the region 1.7◊3.5 eV. The high energy edges of the spectra are at energy 3.4 eV, approximately equal to the gap E_g of GaN at the room temperature. A shoulder at 3.2 eV corresponds to the energy of E_g-ΔE_A, where ΔE_A - ionization energy of Mg-acceptor. The maxima in the range of 2.6◊2.8 eV correspond to the maxima of injection luminescence spectra. The broad maxima in the range 2.2◊2.3 eV correspond to the well known "yellow band" in n-GaN connected with donor-acceptor pairs and/or double donor radiative recombination [12]. The charged impurity distribution in the lower doped p-type side of the structure was determined from dynamical capacitance measurements (see the method in [11]). From C(V) curves a model distribution of charges, electric fields and an energy diagram of the structures at reverse bias was deduced as shown in Figure 5. The charge concentration on the p-side of the space charge region of the heterojunction is (1◊2)$\cdot 10^{18}$ cm^{-3} (a width of 11 nm), on the n-side - of $1\cdot 10^{19}$ cm^{-3} (a width of 1.5 nm), there are compensated quasi-neutral layers (10◊11 nm) adjacent to the active layer (2.5◊4 nm). It is necessary to introduce into the model charged walls on the heterointerfaces to describe the capacity measurements. The electric field in the active layer InGaN is quite high - of $E \approx 10^7$ V/cm, the fields in the adjacent layers - of $E \approx$ 2◊4$\cdot 10^6$ V/cm.

3. Discussion.

The tunnel component of the reverse current can be described by the theory of the J(V) characteristics of highly doped abrupt p-n-junctions in the direct-bandgap semiconductors [13]:

$$J \sim (V-V_k)\exp(B(e|V|/2E_g)),\ B = (\pi/2^{3/2})(2m_{cv}^*/h^2)^{1/2}(E_g^{3/2}/e\boldsymbol{E});\ m_{cv}^* = m_c^* m_v^*/(m_c^* + m_v^*); \quad (2)$$

where V_k is a contact potential, E_g - effective energy gap, m_c^*, m_v^* - effective masses. Taking the parameters m_c^*=0.22 m_0; m_v^*=0.54 m_0, E_g.=3.4 eV, we have estimated the electric field in the active region: $\boldsymbol{E} \approx 2\cdot 10^7$ V/cm (at the experimental values of V_k = 3.2 eV, E_J = 0.86◊0.9 eV), see Figure 1.

The threshold for impact ionization can be connected with the effective concentration of charged impurities in the p-n-junction by the empirical equation [14]:

$$|V_{th}| = 60\,(E_g/1.1)^{3/2}\,(N/10^{16})^{-3/4}. \quad (3)$$

Taking the parameters E_g = 3.4 eV, $|V_{th}|$= 11.5 V, we receive from this equation a value of $N \approx N_A \approx 1\cdot 10^{18}$ cm^{-3}. This value is in accordance with the analysis of capacitance measurements and an evaluation of electric field distribution [3] [5].

The impact ionization is due to electrons tunneling from valence band of the p-side of the structure through the active region of InGaN, subsequent drift in the electric field to the adjacent quasi-neutral and charged n-layer of the structure and receiving an energy of about $3E_g$ sufficient for impact ionization.

The impact ionization coefficient of the electrons can be assumed great in comparison with that of holes, $\alpha_n >> \alpha_p$. In order to evaluate α_n the mean-free paths of hot electrons λ_{fr} and effective phonon energies $k\theta$ are to be estimated taking into account additional high energy extreme in the conduction band. The next extreme between L and M points are at 5.5 eV and the next Γ valley is at 5.6 eV (see Figure 6).

It seems that the changes in the slopes near |V| = 5◊6 V are connected with a probability of high energy electrons to get into Γ-point extreme with high effective masses. The problem of hot electrons in GaN is far from clear.

We can describe the results assuming that the electron-hole pairs are divided by the electric field in the time of $w/v_T \approx 10^{-13}$ ◊ 10^{-14} s ($v_T \approx 2 \cdot 10^7$ cm/s) and only a small part of the electrons can come to the external boundary of the space charge n-region. If the radiative lifetimes are of 10^{-9} s, only a small part of the pairs can recombine radiatively in the structure. So we can understand why the efficiency of the breakdown luminescence is very low.

The spectral maxima in the region of 2.2◊2.3 eV connected with donor-acceptor pairs and/or double donor radiative recombination were seen in the n-GaN [12] [15]. This is an evidence that the most part of radiative recombination is due to electrons created near the n-side of the structure. This recombination is caused by some structural defects; high electric fields and impact ionization are concentrated near defects.

The shoulder at 3.2 eV can be described by optical transitions connected with Mg-acceptors. It means that part of the holes created by impact ionization can recombine with electrons in the conduction band on the p-side of the structure.

4. Conclusions

1. Avalanche breakdown luminescence spectra were detected in blue LEDs based on the InGaN/AlGaN/GaN p-n-heterostructures at reverse voltages about 11◊12 V $\approx 3E_g$ with an intensity of about 6 orders of magnitude lower than injection luminescence spectra. The high energy edge of the spectra corresponds to energy gap of GaN, E_g.=3.4 eV.

2. There are high electric fields in the active InGaN layers of the InGaN/AlGaN/GaN heterostructures, up to 10^7 V/cm. In the adjacent compensated layers the fields are of (2◊4)$\cdot 10^6$ V/cm. Tunnel component of the current dominates at reverse bias < 10 V; tunneling electrons initiate impact ionization at reverse bias $\approx 3E_g$. Special points in current-voltage characteristics near V = - (5◊6) V are connected with higher energy extreme in the conduction band of GaN.

3. A low efficiency of the breakdown luminescence can be understood because of the division of electrons and holes by high electric fields. Broad luminescence band (2.14◊3.4 eV) corresponds to the recombination of carriers mostly on the external boundaries of the space charge regions.

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References

[1] S. Nakamura, M. Senoh, N. Iwasa, S. Nagahama, T. Yamada, T. Mukai, *Jpn. J. Appl. Phys.* ***34***, L1332-L1335 (1995).

[2] K. G. Zolina, V. E. Kudryashov, A. N. Turkin, A. E. Yunovich, Shuji Nakamura , *MRS Internet J. Nitride Semicond. Res.* ***1***, 11 (1996).

[3]A.N.Kovalev, V.E.Kudryashov, F.I.Manyachin, A.N.Turkin, K.Zolina, A.E.Yunovich, “Electrical properties and luminescence spectra of InGaN/AlGaN/GaN light-emitting diodes», *Abstr. of 23rd Intern. Symp. on Semicond. Compounds*, ISCS-23, S.-Petersburg, 03.P3.04, 93 (Sept. 1996)

[4] K. G. Zolina, V. E. Kudryashov, A. N. Turkin, A. E. Yunovich, unpublished (1997).

[5]A.E.Yunovich, A.N.Kovalev, V.E.Kudryashov, F.I.Manyachin, A.N.Turkin, K.Zolina, “Tunnel effects in luminescence spectra of InGaN/AlGaN/GaN light-emitting diodes», *Abstr. of MRS Fall Meeting 1996*, Sympos. N, Boston,N 9-37, 347 (Dec. 1996)

[6] J. I. Pankove, E. A. Miller, J. E. Berkeyheiser, *J.Lumin.* ***5***, 84 (1972).

[7]J.I.Pankove, M.Lampert, “Model for Electroluminescence in GaN», *Phys. Rev. Letters*, 33(6), 361, (1974)

[8]L.N.Mihailov, U.K.Shalabutov, M.D.Shagalov, V.G. Sidorov, L.N.Vasilischev,»Blue - violet GaN light-emitting diodes», *Fiz. i Techn. Poluprov.*, 9(9), 1808 (1975) (in Russian, English translation in Semiconductors)

[9]V.A.Dmitriev, N.I.Kuznetsov, K.G.Irvine, C.H.Carter,»Electric breakdown in nitride pn junction», *Mater. Res. Soc. Symp. Proc.,* 395, 909, (1996)

[10] R. P. Vaudo, I. D. Goepfert, T. D. Moustakas , D. M. Beyea, T. J. Frey, K. Meehan , *J. Appl. Phys.* ***79***, 2779-2783 (1996).

[11] R. J. Molnar, R. Singh, T. D. Moustakas , *Appl. Phys. Lett.* ***66***, 268-270 (1995).

[12]D.M.Hoffmann, D.Kovalev, G.Steude, D.Volm, B.K.Meyer, C.Xavier, T.Monteiro, E.Pereira, E.N.Mokhov, H.Amano, I.Akasaki, “2.2 eV luminescence in GaN», *Mater. Res. Soc. Symp. Proc.,* 395, 619, (1996)

[13]G.E.Picus. “Theory of semiconductor devices», Moscow, “Nauka», 347, (1965) (in Russian)

[14]Sze, S., “Physics of semiconductor devices», Vol. 1

[15] F. A. Ponce, *MRS Bull.* ***22***, 51-57 (1997).

[16] W. E. Carlos , J. A. Freitas, Jr., M. Asif Khan, D. T. Olson, J. N. Kuznia , *Phys. Rev. B* ***48***, 17878-17884 (1993).

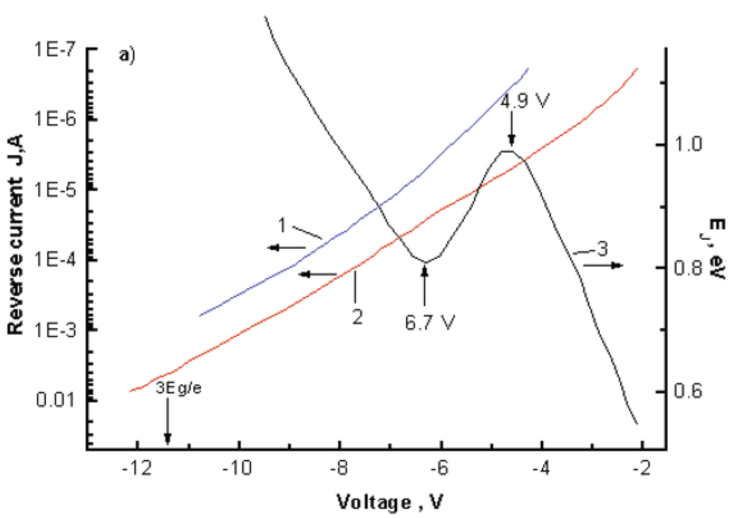

Figure 1. Reverse current-voltage curves of a blue diode (N3); 1 - T=77 K, 2 - T=300 K, 3 - E_J=dV/d(lnJ), T=300 K.

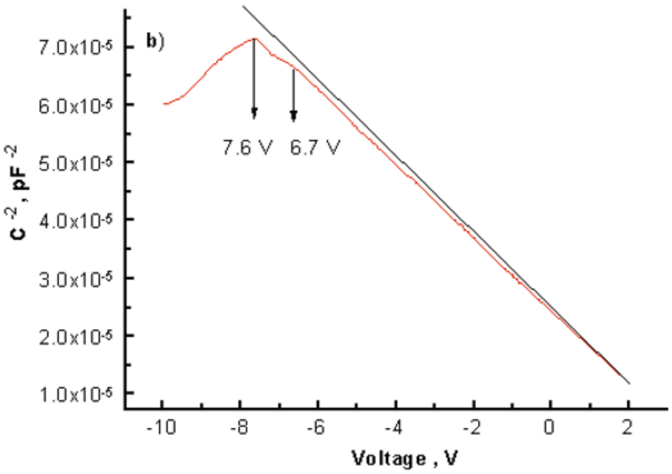

Figure 2. Reverse capacitance-voltage curves of a blue diode (N3).

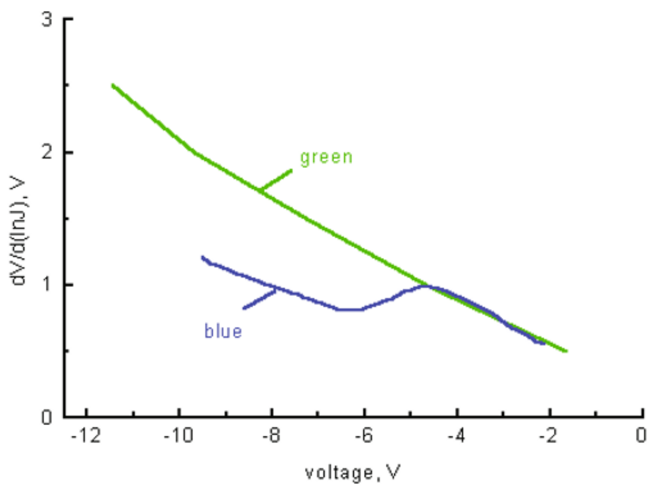

Figure 3. Reverse current-voltage derivative for blue and green LEDs.

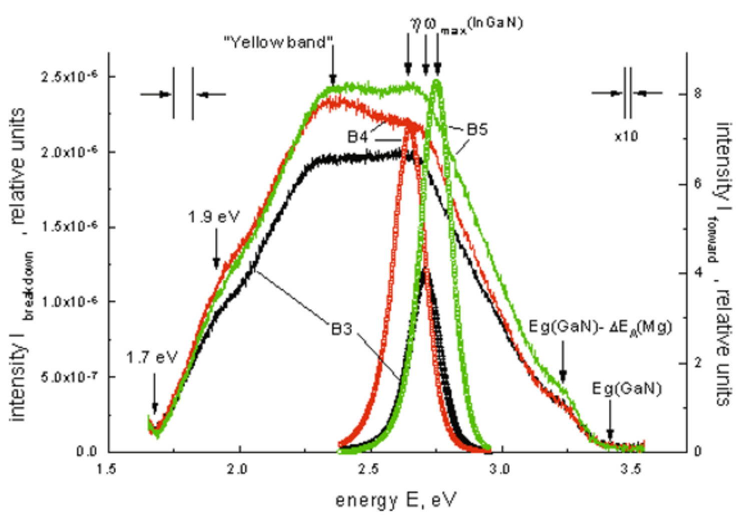

Figure 4. Avalanche breakdown luminescence spectra of blue InGaN/AlGaN/GaN LED's; J = -4 mA, room temperature.

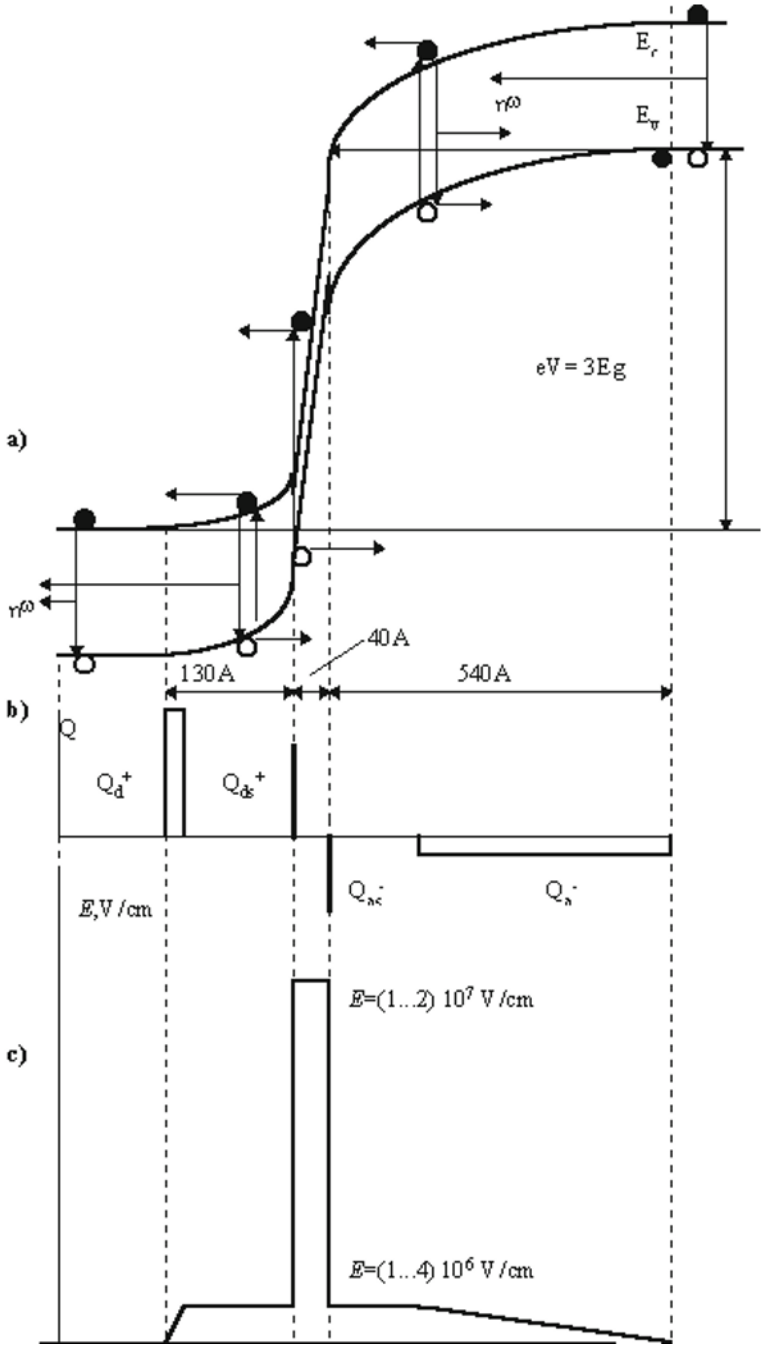

Figure 5. The energy diagram (a) , the model distribution of charge (b) and electric field (c) of the structure at the reverse bias.

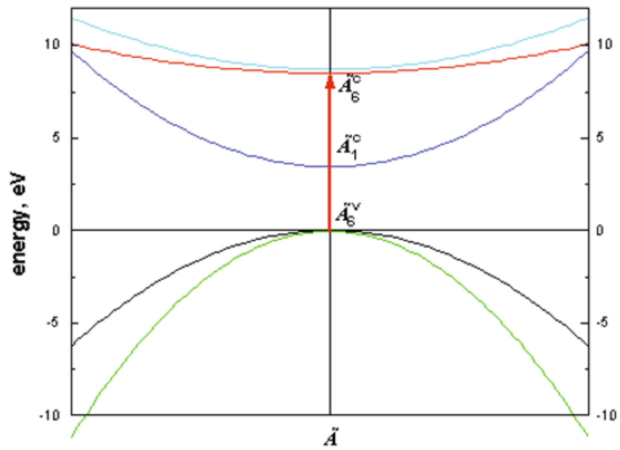

Figure 6. The energy bands involved in the five-band **k·p** calculation. [16]