Electroluminescence of composite channel InAlAs/InGaAs/InP/InAlAs high electron mobility transistor

N. Cavassilas,[a] F. Aniel, P. Boucaud, and R. Adde
Institut d'Electronique Fondamentale, UMR CNRS 8622, Université Paris XI, 91605 Orsay Cedex, France

H. Maher, J. Décobert, and A. Scavennec
OPTO+, France Telecom/CNET, GIE, Route de Nozay, 91460 Marcoussis, France

(Received 4 May 1999; accepted for publication 23 November 1999)

An experimental investigation of impact ionization by electroluminescence in composite channel lattice-matched InAlAs/InGaAs/InP/InAlAs high electron mobility transistors (HEMTs) is presented. In these transistors, an InP subchannel layer is added to the InGaAs channel. Radiative recombinations at two different energies are observed, characteristic of recombinations in the InGaAs channel and at the InP/AlInAs interface. The bias-dependent electroluminescence line intensities are used to analyze the role played by the InP layer for relaxing the hot carriers. A large fraction of electrons in the InGaAs channel of the composite HEMT is transferred to the InP subchannel in the high field gate-drain region. © *2000 American Institute of Physics.* [S0021-8979(00)06105-3]

I. INTRODUCTION

Impact ionization generates electron–hole pairs due to very hot carriers in the high electric field regions of semiconductor devices. It is a well-known process in both field-effect and bipolar transistors which limits their maximum operating voltage. The phenomenon is all the more detrimental in InGaAs channel based high electron mobility transistors (HEMTs) because the energy threshold required for ionization is very low due to the small band gap of $In_{0.53}Ga_{0.47}As$. Electrons and holes created by impact ionization can recombine radiatively, giving rise to the so-called electroluminescence (EL). EL spectroscopy is a sound diagnosis of impact ionization to probe both the localization and the energy distribution of carriers versus bias conditions.[1]

In composite channel InGaAs HEMTs, an InP subchannel layer is added to the InGaAs channel.[2] Therefore a significant fraction of hot electrons can transfer from the InGaAs channel to the InP layer before they reach the threshold of ionization and the mean kinetic energy of these carriers is reduced. The impact ionization energy threshold in InP is higher than in InGaAs due to the wider band gap energy and the larger electron effective mass. These factors contribute to decreased impact ionization effects in the transistor, as illustrated by a smaller gate excess current.[3] The question is to which extent electrons transfer to the InP subchannel?

In this paper, we report on EL spectroscopy in composite channel InAlAs/InGaAs/InP/InAlAs HEMT as a function of device temperature and bias conditions. We discuss the possible occurrence of impact ionization in the different layers, the vertical and lateral localization of electron–hole recombination processes in the HEMT structure. The EL spectra and the influence of the InP layer are discussed as a function of gate and drain biases and the analysis shows that electrons are indeed transferred to the InP subchannel in the high field region of the transistor.

II. SAMPLE AND EXPERIMENTAL SETUP

Composite channel transistors have been designed as shown in Fig. 1. The multilayer structures have been grown by metalorganic vapor phase epitaxy.[4] The so-called composite channel is made of two different layers: a 10 nm thick $In_{0.53}Ga_{0.47}As$ layer and a 30 nm thick nonintentionally doped InP subchannel layer. An undoped InAlAs buffer separates the channel from the semi-insulating InP substrate. The gate is deposited on a 30 nm thick δ-doped InAlAs barrier layer. The InGaAs cap layer is undoped. Figure 2 shows a schematic description[5,6] of the conduction and valence bands of the structure, obtained using a numerical simulation of Poisson equation.

A chip with several transistors is placed in a specially developed cryostat designed for both electric (static, pulsed and microwave) and optical characterizations. Movable coplanar probes allow electrical contacts on the selected device. The luminescence emitted by the electrically driven device exits from the cryostat through an optical window above the chip. The luminescence is focused on the entrance slit of a 0.64 m monochromator and detected with a liquid nitrogen cooled germanium detector.[7]

III. COMPOSITE CHANNEL HEMT CHARACTERISTICS

A small breakdown voltage is a common feature of standard InAlAs/InGaAs/InAlAs/InP HEMTs. The use of an undoped InGaAs cap layer is known to enhance the breakdown voltage.[8] Another way to improve the breakdown voltage is the composite channel structure. The on-state breakdown for the devices investigated here is 5 V, as compared with 3.5 V in standard HEMTs.[1] The present 0.8 μm gate length tran-

[a]Author to whom correspondence should be addressed; electronic mail: nicolas.cavassilas@ief.u-psud.fr

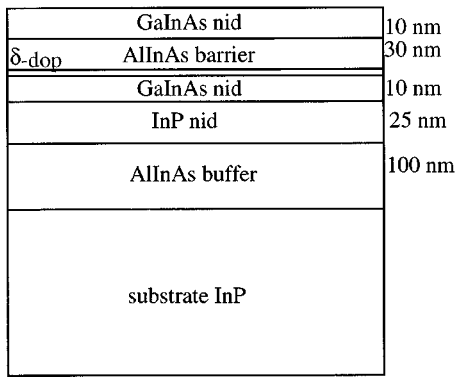

FIG. 1. Layer structure of the composite channel HEMT.

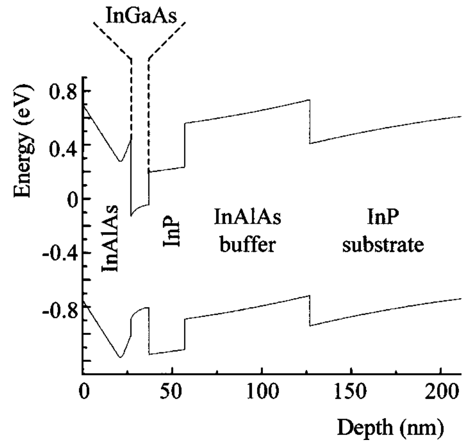

FIG. 2. Conduction and valence bands of the composite channel HEMT calculated by numerical simulation of Poisson equation.

sistors exhibit a threshold voltage $V_{th} = -1$ V, a maximum transconductance $g_{m\,max} = 300$ mS/mm, $I_{DSS} = 400$ mA/mm, a maximum extrinsic cutoff frequency of 40 GHz, a maximum $F_{max} = 110$ GHz, and a relatively weak gate leakage current under normal bias conditions. These performances are at the state of the art for such long gate devices.[4]

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Description of the electroluminescence spectrum

The experimental results presented here correspond to a single representative device, which allows useful comparisons relative to EL intensities. The drain voltage was limited to $V_{DS} = 4$ V in the experiments and all spectra shown here are at $V_{DS} = 3$ V.

Figure 3(a) shows typical EL spectra measured as a function of energy at the two temperatures of 300 and 20 K, under bias conditions corresponding to open channel operation ($V_{DS} = 3$ V, $V_{GS} = 0$ V). The gate bias is close to the value that gives the maximum EL intensity.

The observed EL spectra extend over the energy domain from the cooled Ge photodetector 0.7 eV cutoff energy, up to 1.4 eV. No EL signal with a significant intensity is observed between 1.4 and 1.6 eV at any temperature and bias condition under 3 V drain voltage. The drain voltage threshold beyond which an EL signal is observed is 2 V. Two main peaks centered, respectively, near 0.8–0.85 eV and 1.25 eV are observed in Fig. 3(a). The spectra are not corrected for the equipment spectral response. If one takes into account the spectral response of the cooled Ge detector and the spectrometer efficiency, the intensity of the 1.25 eV peak must be multiplied by a factor of 5 as compared to the 0.85 eV peak. The total integrated EL intensity, which accounts for the correction factors, is shown in Fig. 3(b) versus temperature, together with the two integrated peak intensities.

One also observes a shift of the 0.85 and 1.25 eV transition peak energies toward lower energies, with the increase of temperature. This redshift corresponds to the reduction of the band gap energies with temperature.

B. Where does impact ionization occur in composite channel InGaAs HEMTs

The voltage biases are small and we can assume that in each layer only Γ valley electrons can ionize valence electrons with the creation of electron–hole pairs. The latter holes do not have enough energy to ionize other valence band electrons.

Impact ionization can occur in the InGaAs channel layer (energy gap 0.75 eV at 300 K and 0.802 eV at 77 K), in the InP subchannel layer (energy gap 1.35 eV at 300 K and 1.42 eV at 10 K), and in the InAlAs layer (1.44 eV at 300 K and 1.513 eV at 77 K).[5,6] The ionization threshold energy and the effective masses, which increase with the energy band gap, are much larger in InP and InAlAs than in InGaAs. Also, ionization coefficients for stationary transport in InP and InAlAs are much smaller than in InGaAs.[9] Impact ionization in the InGaAs layer is therefore expected to dominate, although a small contribution may stem from the InP and InAlAs layers.

We point out the presence of an InAs well transition layer at the InP(subchannel)/InAlAs(buffer) interface. Its thickness is estimated to be 2 or 3 ML (1 ML≈0.3nm). The

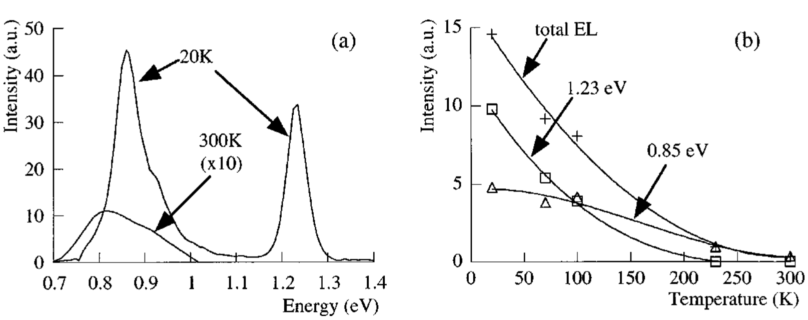

FIG. 3. (a) EL spectrum at 20 and 300 K for $V_{DS} = 3$ V and $V_{GS} = 0$ V. (b) EL intensity vs temperature for $V_{DS} = 3$ V and $V_{GS} = 0$ V.

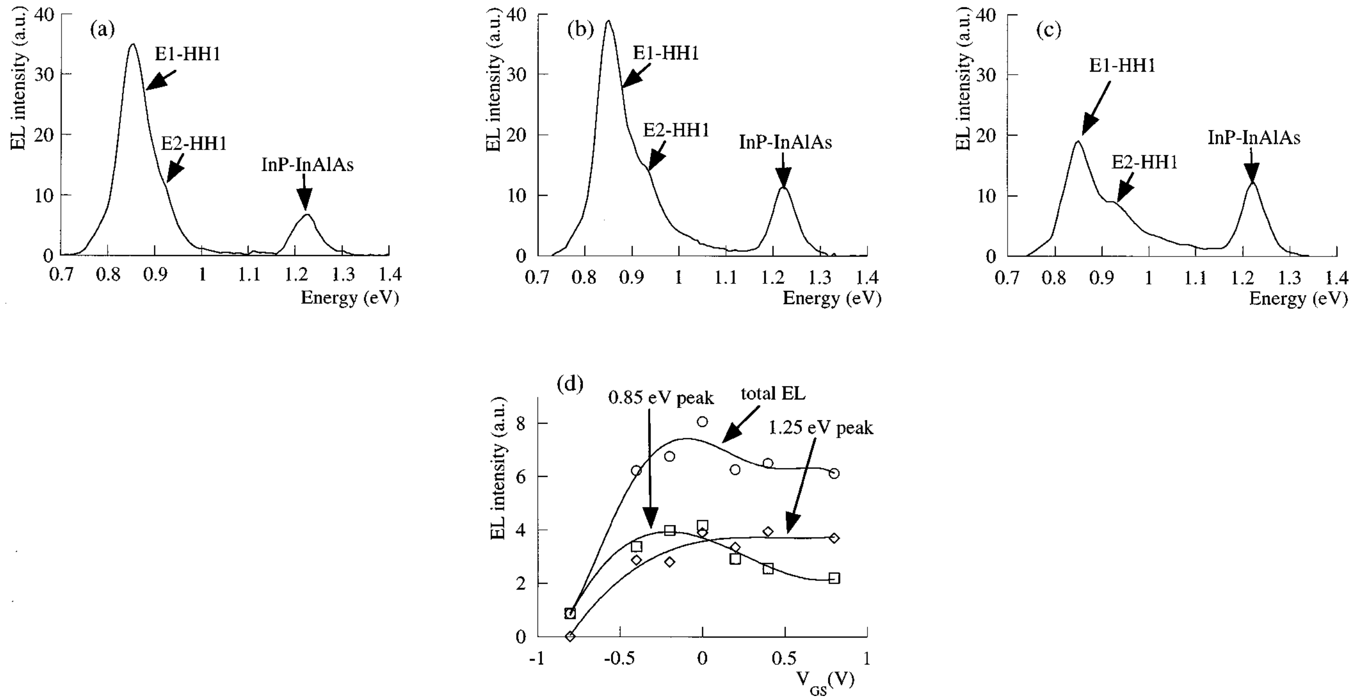

FIG. 4. EL spectra at 100 K for $V_{DS}=3$ V and $V_{GS}=-0.4$ V (a), $V_{GS}=0$ V (b), $V_{GS}=+0.4$ V (c). Integrated EL intensity of each line and of the total EL spectrum vs V_{GS} for $V_{DS}=3$ V (d).

transition energy at 20 K of a 0.8 nm thick InAs well, calculated by solving the Schrödinger equation in the envelope function approximation, is 1.22 eV.[10] Therefore this InAs well transition layer may be involved in an impact ionization process, as it is also reported for an InP channel heterojunction field effect transistor.[11]

On the other hand, impact ionization is expected to take place in the high field gate-drain region of the transistor. The onset of the EL signal occurs at $V_{DS}=2$ V. The saturation voltage of the current–voltage characteristics is nearly $V_{DS}=0.6$ V at $V_{GS}=0$ V. This means that the voltage drop in the gate–drain region at $V_{DS}=2$ V is limited to 1.4 V, and some ballistic electrons may reach 1.4 eV at the observed threshold of ionization. Consequently, a 1.4 eV energy is large enough for the occurrence of impact ionization in the InGaAs channel and at the InP/InAlAs interface, but it remains too small in the other layers.[9]

The EL spectra measured for different transistors between $V_{DS}=2$ V and $V_{DS}=4$ V (not shown) have very similar shapes versus energy at all temperatures, without the appearance of any specific peak above 1.4 eV. We can conclude that at $V_{DS}=4$ V, impact ionization occurs in the InGaAs channel and in the InAs well transition layer at the InP/InAlAs interface for this transistor technology. As the device has no *p*-doped material, holes which recombine radiatively with conduction electrons and produce the EL spectrum are necessarily created by impact ionization in the InGaAs channel and possibly in the InAs well transition layer at the InP/InAlAs interface.

In conclusion, electrons in the composite channel HEMT are expected to transfer from the InGaAs channel to the InP channel as they drift under the gate or in the gate–drain access before avalanche multiplication leads to breakdown. Impact ionization, localized in the gate–drain region, occurs in the InGaAs layer, due to electrons in that part of the channel, and at the InP (channel)/InAlAs(buffer) interface rather than in the InP channel layer, because the effective band gap at the interface is much smaller than the InP band gap.

C. Vertical localization of radiative recombinations

We have studied the EL spectrum as a function of gate bias at 100 K, which corresponds to good signal to noise ratio conditions. The shape of the EL emission lines does not change noticeably with temperature. Figures 4(a), 4(b), and 4(c) show an example of uncorrected EL spectra at 100 K and $V_{DS}=3$ V for the three gate biases -0.4, 0, and $+0.4$ V. Figure 4(d) shows the corrected integrated intensity of each line and of the total EL spectrum as a function of gate voltage. The total EL signal can be observed from -0.8 V, close to the -1 V threshold gate voltage. The spectra indicate that the 0.85 and 1.25 eV peaks have comparable intensities over a large V_{GS} range.

The 0.85 eV peak is attributed to direct recombination in the InGaAs quantum well of electrons in the first sublevel $E1$ and of holes in the HH1 sublevel. This assignment is confirmed by numerical simulations which show that, in a 10 nm thick InGaAs well, the $E1-$HH1 energy difference at 100 K is 0.85 eV. One also observes the recombination between the second sublevel $E2$ and the sublevel HH1 at 0.93 eV, which is clearly visible at 100 K for positive V_{GS} [Fig. 4(c)].

The energy value of the peak at 1.25 eV indicates that it is associated with indirect spatial recombinations at the InAlAs(buffer)/InP(subchannel), or possibly at the InAlAs(buffer)/InP(substrate) interface, between electrons in

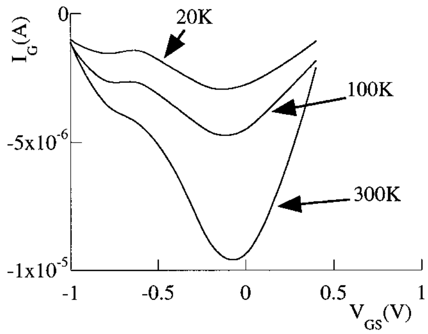

FIG. 5. Gate current vs gate voltage at temperatures 20, 100 and 300 K for $V_{DS}=3$ V.

the InP conduction band and holes in the valence band of the InAlAs buffer (see Fig. 2). The energy at 1.25 eV confirms an InAs well with a 2 or 3 ML thickness. The recombination should be better labeled as a mixed type I–II. The recombination process is enhanced by the presence of the InAs well transition layer at the interface, which increases the integral of the overlap of the electron and hole envelope wave functions. This integral is equal to 0.2 and 0.9, respectively, for 2 and 3 ML thick wells.[10] The observation of the 1.25 eV peak is very important as it confirms the quantitative transfer of hot electrons from the InGaAs channel to the InP subchannel layer. This transfer avoids on-state breakdown at low drain bias as compared with classical AlInAs/InGaAs/InP HEMTs.

D. Discussion

In the following we consider impact ionization only in term of qualitative efficiency. This is because conventional ionization rates lose their meaning due to nonstationary transport of electrons in the device channel and subchannel, and to the poor knowledge of the mixed type I–II InP/InAlAs interface.

We comment first on the changes of EL line intensities with temperature. Figures 3(a) and 3(b) show that the EL transition intensities drop rapidly when the temperature increases from 20 to 300 K; for instance the integrated intensity of the 0.85 eV line decreases by a factor of 40. However, the efficiency of nonradiative recombination mechanisms increases when the temperature rises, as compared with radiative ones, and one cannot draw any conclusions about the sign of the temperature variation of the InGaAs ionization coefficient, only from the intensity variation of the EL data. On the other side holes have a thermionic emission probability which rises with temperature and a larger fraction of them in the InGaAs channel is injected through the InGaAs/InAlAs barrier and reaches the gate metallization. This can explain the increase of gate current with temperature which is shown in Fig. 5. Again the gate current variation does not allow us to resolve the sign of the variation of the impact ionization with temperature.

It is also worth noting the very fast decrease of the 1.25 eV signal intensity with temperature. Due to the increase of the phonon scattering rate with temperature, the electron concentration in the InP subchannel decreases. Besides, holes have a thermionic emission probability which rises with temperature, and a larger fraction of them at the InP/InAlAs interface are injected through the InP barrier in the InGaAs channel. This hole transfer induces a stronger decrease of the 1.25 eV signal with increasing temperature than for the 0.85 eV signal.

We now comment on the longitudinal localization between source and drain of electroluminescence at 1.25 eV. EL at the band gap energy in InGaAs channel transistors is often attributed to electron–hole recombination in the source region of the transistor.[13] We point out that in the composite InGaAs HEMT and at low drain bias (3 V), there is a weak concentration of electrons in the source region of the InP subchannel. Moreover the large intensity of the 1.25 eV recombination peak is a strong indication that holes have been created at the InP/InAlAs interface in a region of large current density. This suggests that in the composite InGaAs HEMT, electroluminescence at 1.25 eV occurs in the gate–drain access area where impact ionization takes place.

Finally we consider the correlations between the changes of EL line intensities with gate bias and the device electric properties. First the intensity dependence of the 0.85 eV EL line on gate bias correlates rather well with the gate current dependence on gate voltage as illustrated in Fig. 6(a). This has been already reported for single channel InGaAs HEMTs on InP.[1] Holes created in the InGaAs channel drift back partly toward the source, and are injected partly through the barrier toward the gate electrode (excess gate current) or the surface. The difference between the two curves at positive gate voltages has been demonstrated already as attributable to real space transfer of electrons, compensating for the hole current.[12] The concentration of holes created in the InGaAs channel is maximum for $V_{GS}=0$ V. In this voltage range, there is both a high electron density in the InGaAs channel and a large enough electric field in the gate–drain access.

On the other side the 1.25 eV EL line intensity and the drain current have a similar dependence on gate voltage over

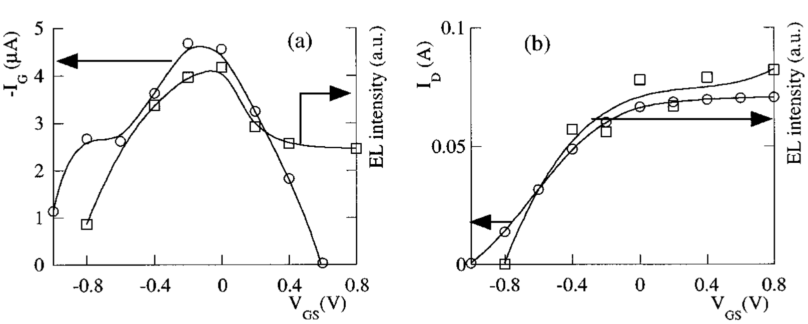

FIG. 6. (a) Gate current (circle) and EL intensity of the 0.85 eV line vs (square) gate voltage for $V_{DS}=3$ V at temperature 100 K. (b) Drain current (circle) and EL intensity of the 1.25 eV line (square) vs gate voltage for $V_{DS}=3$ V at temperature 100 K.

a wide bias range as show in Fig. 6(b). We have seen before that the 1.25 eV EL intensity pictures impact ionization at the InP/InAlAs interface. Then impact ionization at this interface is strongly governed by I_D, meaning that the drain current is for a large part an electron current flowing near the InP/InAlAs interface. On the other side both the 0.85 and 1.25 eV EL peaks have intensities of the same magnitude, which means that comparable numbers of holes are created by impact ionization while the ionization efficiency of the InAlAs/InP interface was found to be much lower than that of the InGaAs channel. This indicates that a local electron concentration higher near the InAlAs/InP interface than in the InGaAs channel compensates for a lower ionization efficiency. This quantitative transfer of hot electrons from the InGaAs channel to the InP subchannel layer in on-state channel conditions, prevents avalanche breakdown at low drain bias as mentioned previously.

V. CONCLUSION

The experimental results presented here show that, at least for long gate devices (0.8 μm), a large fraction of electrons in the InGaAs channel of the composite HEMT is transferred in the InP subchannel in the high field gate drain region. This is shown by the intensity dependence on gate bias of the parasitic EL signal associated with the subchannel buffer interface which follows rather closely the source–drain current. The changes of the two EL peak intensities and of the gate current are consistent with the increase of radiation recombination and the decrease of thermionic emission as the temperature is lowered, so that there is no clear conclusion on the dependence of impact ionization on temperature in these transistors. This combined investigation of electroluminescence and excess gate current in InAlAs/InGaAs/InP/InAlAs/InP composite channel HEMTs improves the picture of the physical phenomena in these transistors and shows that the InP subchannel performs appropriately.

ACKNOWLEDGMENTS

The authors wish to thank Georg. Post and Aline Falcou for help in HEMT processing and Astrid Gautier-Lévine for results on AlInAs/InP interface ionization.

[1] A. Sylvestre, F. Aniel, P. Boucaud, F. H. Julien, P. Crozat, A. De Lustrac, R. Adde, Y. Jin, and J. P. Praseuth, J. Appl. Phys. **80**, 464 (1996).
[2] T. Enoki, K. Rai, A. Kohzen, and Y. Ishii, IEEE Trans. Electron Devices **42**, 1413 (1995).
[3] C. Ladner *et al.*, Proceedings of IPRM'98, Tsukuba, Japan, 1998.
[4] H. Maher, J. Décobert, A. Falcou, M. Le Pallec, G. Post, Y. I. Nissim, and A. Scavennec, IEEE Trans. Electron Devices **46**, 32 (1999).
[5] *Properties of Lattice-Matched and Strained Indium Galium Arsenide*, edited by Pallab Bhattacharya (University of Michigan, Press).
[6] S. Adachi, *Physical Properties of III-V Semiconductor Compounds* (Gunma University Press, Kiryu-shi, Japan).
[7] F. Aniel, P. Boucaud, A. Sylvestre, P. Crozat, F. H. Julien, R. Adde, and Y. Jin, J. Appl. Phys. **77**, 2184 (1995).
[8] J. Dickmann, H. Haspeklo, A. Geyer, H. Daembkes, H. Nickel, and R. Losch, Electron. Lett. **28**, 647 (1992).
[9] J. Bude and K. Hess, J. Appl. Phys. **72**, 3554 (1992).
[10] D. Vignaud, X. Wallart, F. Mollot, and B. Sermage, J. Appl. Phys. **84**, 2138 (1998).
[11] A. Gauthier Levine, R. Tessier, A. Nezzari, E. Elchuri Rao, J. Decobert, J. L. Pelouard, and A. Scavennec, Jpn. J. Appl. Phys (to be published).
[12] G. Berthold, E. Zanoni, C. Canali, M. Pavesi, M. Pecchini, M. Manfredi, S. R. Bahl, and J. A. Del. Alamo, IEEE Trans. Electron Devices **42**, 752 (1995).
[13] N. Shigekawa, T. Enoki, T. Furuta, and H. Ito, IEEE Electron Device Lett. **16**, 515 (1995).