Sign of the piezoelectric field in asymmetric GaInN/AlGaN/GaN single and double quantum wells on SiC

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ABSTRACT

We study both GaInN/GaN/AlGaN quantum wells with an asymmetric barrier structure grown on SiC substrate and GaN/AlGaN asymmetric double quantum well (ADQW) structures. In the first case, a time-resolved study reveals an enhanced oscillator strength when the AlGaN barrier is on top of the GaInN quantum well. In comparison to our previous study of the same structure grown on sapphire, we find that the sign of the field is the same in both cases: the field points towards the substrate. In the case of ADQW, we observed not only intrawell transitions of both a 4 nm and a 2 nm QW separated by a 2.5 nm AlGaN barrier but also an interwell transition between the two QWs in the photoluminescence. The lifetimes and emission energies of the transitions can be well explained by the existence of the piezoelectric field built in the QWs.

INTRODUCTION

GaInN/AlGaN/GaN-based quantum wells (QWs) have played a key role in the rapid development of short-wavelength light emitters [1]. To explain the puzzling optical properties of the quantum wells, the piezoelectric field effect has been recently discussed actively [2,3,4,5]. In this work, we explore the effect in more detail studying two structures designed specially: first, asymmetric barrier structures, i.e., a GaInN quantum well sandwiched between an AlGaN and a GaN layer, and secondly, GaN/AlGaN asymmetric double quantum well structures. The asymmetry introduced in hese structures exhibits clearly the dominating influence of the piezoelectric field on the optical transitions in the quantum wells.

EXPERIMENTAL

Our samples were grown on (0001)-oriented SiC substrates using low-pressure metalorganic vapor phase epitaxy (LP-MOVPE). The GaInN layers were grown below temperature of 800°C with N_2 as a carrier gas. The growth temperature of GaN and AlGaN layers was 1000°C. Reciprocal space mapping of X-ray diffraction intensity shows that GaInN grown on GaN buffers is coherently strained up to thickness of some 100 nm [6]. A nominally undoped 7 nm GaInN QW is sandwiched between asymmetric barrier layers, which consist of a 300 nm GaN buffer layer, a 60 nm GaN cap layer, and a 20 nm AlGaN layer below or above the quantum well (see Fig. 1). The asymmetric double quantum well structure consists of a 2 nm and a 4 nm GaN QW, which are grown in succession on a 700 nm AlGaN buffer layer and separated by a 2.5 nm AlGaN layer. Time-resolved photoluminescence (TRPL) spectroscopy with resonant excitation of the quantum wells was performed at 5 K using a setup already described elsewhere [3].

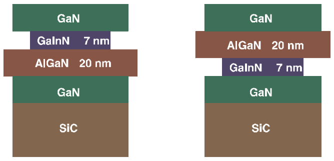

Fig. 1. *Schematic pictures of sample structure of GaInN/GaN quantum wells with an AlGaN barrier.*

RESULTS

Asymmetric barrier structure on SiC substrate

In this section, we study GaInN/GaN QWs grown on SiC substrates with an additional AlGaN barrier above or below the quantum well. Fig. 2 shows low-temperature photoluminescence spectra of two QWs with asymmetric structure and a simple QW without the AlGaN barrier. The simple QW has an emission maximum at 3.08 eV and a phonon replica is recognizable. The sample with an AlGaN barrier below the quantum well exhibits no emission correlated with the GaInN layer, but shows a broad emission band around 2.67 eV emitted by the SiC substrate. In contrast, the sample with an AlGaN barrier above the quantum well shows an emission, and its maximum lies higher than that of the simple QW. A more detailed picture is given by decay traces at the respective luminescence maxima (see Fig. 3). We find that the luminescence intensity of the sample with an AlGaN barrier above the quantum well decays much faster than that of a simple quantum well without an AlGaN layer. At long delay time, we obtain a decay time of 25 ns for the former and 100 ns for the latter.

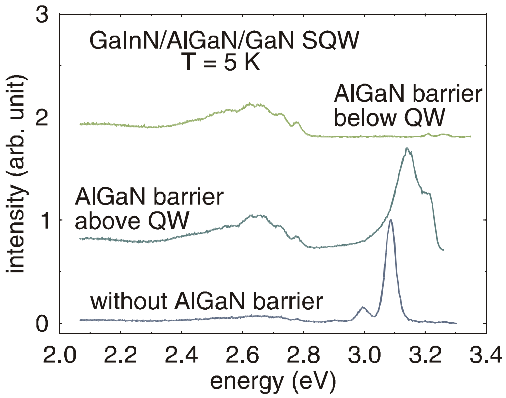

Fig. 2. *Time-integrated low-temperature photoluminescence spectra of GaInN/GaN quantum wells with and without an additional AlGaN barrier.*

The origin of the difference induced by the introduction of the additional AlGaN barrier can be well explained by the existence of a piezoelectric field in the quantum well: if there were no electric field in the quantum well, the quantum wells with asymmetric structure would show identical optical properties. In the presence of a piezoelectric field, the additional AlGaN barrier leads to increased electron confinement and oscillator strength when it is placed where electrons are pushed by the electric field. If the AlGaN layer is grown on the other side of the quantum well, we expect a decrease of electron confinement and oscillator strength, leading to quenching of the optical transitions.

The sample with an AlGaN barrier on top of the quantum well exhibits a decreased lifetime compared with the simple quantum well, which indicates increased oscillator strength in this structure. In addition, the energetic position shifts toward higher energy due to the increased confinement energy. Therefore, our experimental results indicate directly that the piezoelectric field points towards the substrate.

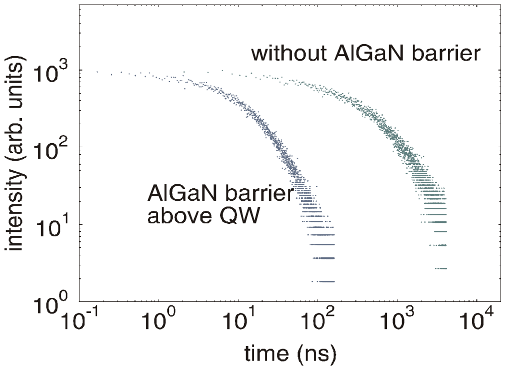

Fig. 3. *Photoluminescence decay of GaInN/GaN quantum wells without and with an additional AlGaN barrier above the quantum well.*

It should be noticed that the additional AlGaN layer is grown at the same growth temperature of GaN layers to avoid a different interface quality among samples due to different growth temperatures. The interface effect therefore is not large enough to cause the observed difference of optical properties among samples.

It is interesting to compare this result with our previous work on the same structure grown on a sapphire substrate. The sample with an AlGaN barrier below the QW grown on the sapphire substrate exhibited a transition that is not quenched, but decays more slowly by 2-3 orders of magnitude than that with an AlGaN barrier above QW, indicating the same results of decreased electron confinement [5]. And we observed that an additional AlGaN barrier above the quantum well enhances the electron confinement in the sample grown on the sapphire substrate. This leads to the conclusion that the direction of the field is not dependent on the choice of SiC or sapphire substrate for structures grown by MOVPE.

We consider now the crystallographic polarity of our samples in relation to the piezoelectric polarity. Principally, there is no conclusive relationship between the crystallographic and piezoelectric polarity. But, guided by the theoretical sign of piezoelectric coefficient [7], the direction of the piezoelectric field in GaInN/GaN QWs is opposite to the [0001]-direction, which indicates that our samples are grown in the [0001]-direction, i.e., with Ga-face polarity. Therefore, the crystallographic polarity is also independent of the choice SiC or sapphire substrate, as is the piezoelectric polarity.

Asymmetric double quantum well

On the basis of the results in the previous section, we study an asymmetric GaN/AlGaN double quantum well grown on a SiC substrate. The two 2 nm and 4 nm

GaN quantum wells are separated by a 2.5 nm AlGaN barrier layer. Low-temperature spectra of the sample are summarized Fig. 4. To start with the time-integrated spectrum (dotted curve), we find a main emission line at 3.44 eV. This line is neighbored by two lines at 3.34 eV and 3.56 eV. It is interesting to notice that the energy differences between the main line and the two lines are similar. Time-resolved measurements reveal a more detailed picture. Fig. 4 shows normalized photoluminescence time-resolved spectra (solid curves) at increasing delay times. One can clearly distinguish three peaks again dominating the spectrum for different delay times. Within approximately 8.7 ns after excitation, the high-energy peak intensity vanishes almost completely and the middle-energy peak dominates the spectrum. With further evolution in time, the low-energy peak takes over the maximum position.

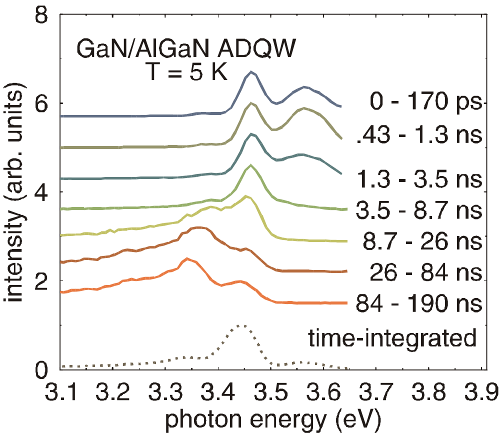

Fig. 4. *Time-integrated and time-resolved photoluminescence spectra of a GaN/AlGaN asymmetric double quantum well.*

A comparison of the decay times of the emission lines is given in Fig. 5. The high-energy peak intensity decays with a lifetime of about 0.3 ns and the middle-energy peak shows a rather increased lifetime of 4 ns. The decay time of the low-energy emission line is dramatically increased up to a time scale in the microsecond range.

Let us now discuss the origin of these peaks. The high- and middle-energy lines can be interpreted as intrawell transitions in the 2 nm and 4 nm quantum well, respectively. The difference of the energy position and the lifetime of these lines is mainly induced by the piezoelectric field in the strained GaN quantum wells as observed earlier [3]. To explain the low-energy line, we take a close look at the band diagram depicted schematically in Fig. 6. The AlGaN barriers are assumed to be unstrained and have no piezoelectric field, while the GaN QWs are under a biaxial

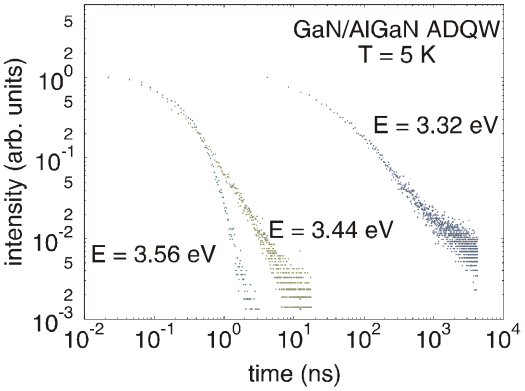

Fig. 5. *Photoluminescence decay of a GaN/AlGaN asymmetric double quantum well.*

compressive strain, which induces a piezoelectric field F_{piezo}. In thermal equilibrium, the global band bending due to background doping gives rise to a depletion region in the AlGaN barriers below the GaN QWs and electrons accumulating in the topmost QW [5]. The resulting space charges partially screen the field in both QWs in an almost homogeneous manner. Since the barrier layer between the two QWs is much thinner than the typical Debye length of several 10 nm, the barrier layer does not carry any significant space charge. Nevertheless, the screening field F_{scr} induces a reverse electric field in the AlGaN barrier. On the other hand, a reduced effective electric field $F_{\mathrm{eff}} = F_{\mathrm{piezo}} - F_{\mathrm{scr}}$ is built in both GaN QWs.

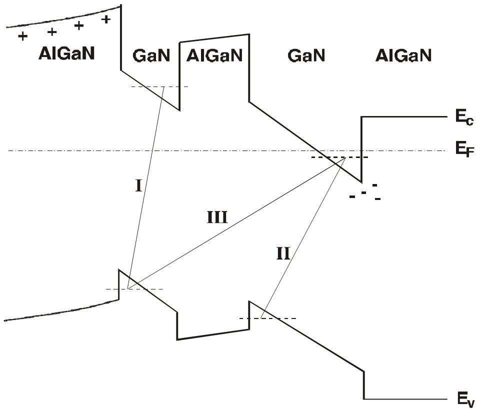

Fig. 6. *Schematic band diagram of an asymmetric GaN/AlGaN double quantum well with the piezoelectric field. Due to Fermi level alignment, the conduction bands of the AlGaN buffer layers are bent upward, and electrons are depleted.*

The effective field F_{eff} affects the energies of the intrawell transitions in the 2 nm and 4 nm QWs, which are labeled with I and II, respectively. The transition energy of QWs which are thicker than 2 nm varies approximately linearly with the well width [3]. Within this approximation, the energy difference between I and II is given as $\Delta E_{\mathrm{I,II}} = F_{\mathrm{eff}} \times \Delta L$, where ΔL is the well width difference of both GaN QWs. On the other hand, we can express the energy difference of the interwell (III) and the intrawell (II) transition as $\Delta E_{\mathrm{II,III}} = F_{\mathrm{eff}} \times L_{\mathrm{I}} - F_{\mathrm{B}} \times L_{\mathrm{B}}$, where L_{I} and L_{B} is the width of the 2 nm GaN QW and of the AlGaN barrier layer, respectively.

Our photoluminescence measurements result in $\Delta E_{\mathrm{I,II}}$ of 120 meV and $\Delta E_{\mathrm{II,III}}$ of 100 meV. A comparison of this observation to the model indicates that the electric field F_{B}, which is induced by a screening field F_{scr} in the AlGaN barrier, is about 10 % of the piezoelectric field F_{piezo}.

Furthermore, the electron-hole separation for the interwell transition (III) can be approximated to the electron-hole separation in a 8.5 nm quantum well. This results in a small overlap of electron and hole wave functions. The lifetime in a microsecond range of the low-energy emission complies well with this expectation. Both the energetic position and the lifetime of the low-energy line can be well understood by the model considering an electric field in the double quantum wells.

The intrinsic electric field has two origins: first, a strain-induced piezoelectric field, and secondly, a spontaneous polarization. Especially, theoretical work predicted that spontaneous polarization in GaN/AlGaN QWs plays a more significant role compared to GaInN/GaN QWs [7]. Our experiments are sensitive to the total field, but cannot distinguish between the piezoelectric and spontaneous contributions.

It should be noticed that the appearance of the interwell transition depends crucially on the redistribution of excess carriers. Without this redistribution each quantum well would be semi-isolated, and only the intrawell transitions would be observed. The TRPL shows that the intrawell transition in the 2 nm QW disappears within about 8 ns. This indicates that the excess electrons in the 2 nm QW escape to the 4 nm QW or recombine with holes on this time scale. In this context, we can expect that the change of the position of the two quantum wells causes a different distribution of excess carriers in the QWs. In this case, the excess electrons in the 4 nm QW escape to the 2 nm QW, which has an effect on the interwell transition of the 4 nm QW.

SUMMARY

A time-resolved study on GaInN/GaN QW with an asymmetric barrier on SiC substrate reveals an enhanced oscillator strength when the AlGaN barrier is on top of the GaInN quantum well. In comparison to our previous work on a structure grown on sapphire, we find that the sign of the field is the same in both cases: the field points toward substrate. In the case of GaN/AlGaN ADQW, we observed an inter- and two intra-well transitions in the photoluminescence, and their lifetimes and emission energies confirm that these transitions are strongly influenced by the piezoelectric field.

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