Surface photovoltage spectroscopy of epitaxial structures for high electron mobility transistors

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AlGaN/GaN high electron mobility transistor, AlGaAs/InGAs/GaAs pseudomorphic HEMT, and InAlAs/InGaAs metamorphic HEMT (MHEMT) epitaxial structures have been characterized using surface photovoltage spectroscopy. The effects of the transistor top and bottom delta-doping levels $\delta_{\text{top}}$, $\delta_{\text{bot}}$, and surface charge $Q_{\text{sur}}$ on the spectrum features have been studied using numerical simulations. Based on the latter, an empirical model has been developed, which allows extraction and comparison of $\delta_{\text{top}}$, $\delta_{\text{bot}}$, and $Q_{\text{sur}}$ and is applicable for both double-sided and single-sided delta-doped structures. Prediction of the final device performance by the model is shown for two MHEMT structures. Devices produced on these structures show maximum drain currents, which correlate well with $\delta_{\text{top}}$ values calculated using the model. © 2003 American Institute of Physics.

For high power high-speed applications due to their high electron mobility of two-dimensional electron gas (2DEG), good thermal isolation, and high breakdown voltage, delta-doping and surface charge are attractive for low-noise applications. InGaAs/GaAs pseudomorphic HEMTs (PHEMTs) are the current “work horses,” widely used for microwave, high speed and power applications.

Surface photovoltage spectroscopy (SPS) is a method, which fulfills most of the demands for comprehensive transistor structure characterization and for incoming wafer inspection. SPS monitors changes in the semiconductor surface work function induced by absorption of monochromatic light, giving rise to surface photovoltage (SPV). A detailed description of this method and its applications may be found in Ref. 10. This technique has been successfully applied for characterization of structures and devices. Recently, Cheng et al. reported on SPS characterization of PHEMT structures. Signals have been observed from every region of the sample. From a line shape fit of the SPV signal with respect to the photon energy, the authors obtain the 2DEG density. The Al composition of the GaAs/AlGaAs superlattice buffer as well as the intersubband transition energies of the buffer and channel layer have been deduced from the experiment. However, the authors do not refer to electrical field and charge distributions in the epitaxial structures with different material composition and different band lineups and their correlation with the final device performance.

In this letter, we present a methodology of contactless characterization of various HEMT structures. This approach is based on deep analysis of HEMT SPV spectra together with numerical simulations of spectral features and empirical modeling. The empirical model is applied to characterization of differences in doping level between various GaN/AlGaN HEMT, MHEMT, and PHEMT structures. dc characterization of final devices has been performed.

HEMT structures have been fabricated by metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) growth techniques. Table I summarizes the material composition and range of doping levels of the struc-

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<th>TABLE I. Materials properties of studied HEMT structures.</th>
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tatures as given by the manufacturer. SPS experiments have been performed in air using a commercial Kelvin probe unit with a sensitivity of $\sim 1$ mV.

The SPV spectra analysis is based on quantitative simulations, numerically solving the Poisson equation, the Schrödinger equation, the continuity equations for electrons and holes and the current equations. Typical HEMT structures are designed in such a way that there are two oppositely directed electric fields in the buffer, a wide layer grown on the substrate that is introduced to prevent substrate defects from reaching the active region of the device, and in the Schottky layer, an undoped layer that separates between the gate and the channel. Thus, the SPV signals from these layers are of opposite signs. The total SPV signal is a combination of the signals from all structure layers. The signal magnitude is a complicated function of light absorption and the electric fields in any absorption region. Absorption of light in the quantum well (QW) creates electron-hole pairs. While electrons are confined within the QW by fields in buffer and Schottky layer, holes are likely to overcome the QW–Schottky layer interface or the QW-buffer interface potential barrier. The holes are swept by the electric field in the buffer or in the Schottky layer direction, contributing to signals with opposite signs. The inset in Fig. 1 shows the simulated SPV signal from the buffer (circles), the Schottky layer (squares) as well as the total signal (solid curve) for a double-sided delta-doped PHEMT structure. In the simulated case, at photon energies below 1.37 eV the signal from the buffer is dominant, which results in a positive total SPV. When the signal from the buffer is saturated, the total SPV changes sign because of the dominating signal from the Schottky layer. The absorption in the buffer is the reason for the second peak formation. In a GaN/AlGaN HEMT structure, a triangular QW is formed at the interface with Schottky layer. Thus, the potential barrier for holes is much smaller in the Schottky layer direction and holes generated by QW absorption are swept toward the Schottky layer, contributing to a dominant positive signal in the QW region of absorption.

Figure 1 shows parts of SPV spectra of a double-sided delta-doped PHEMT structure (solid curve) and two MHEMT structures, $M_1$ (circles) and $M_2$ (squares), which differ in their top delta-doping $\delta_{\text{top}}$ levels. Differences in $\delta_{\text{top}}$ between the structures lead to changes in electric fields distributions and potential profiles, which, in turn, lead to variations of spectral shapes between the structures. At the low energy region, absorption takes place in the QW. At this portion of the spectrum, increasing signals (for PHEMT and M2 spectra) as well as decreasing signals (for $M_1$) are observed. At energies above 1.4 eV, a second peak in the PHEMT spectrum is observed. This feature may be attributed to GaAs absorption. At low photon energies, Fermi filling, due to high electron concentration in the channel, dominates the InGaAs absorption coefficient. This effect significantly changes the absorption coefficient of the QW by blueshifting its edge and reducing its magnitude at higher energies.

Figure 2 shows SPV spectra of a single-sided delta-doped GaN HEMT and a MHEMT (see inset of Fig. 2). The total signal in the QW absorption region is positive. Therefore, SPV spectra of double-sided and single-sided delta-doped structures with different material composition may be fully understood.

The spectra of HEMT structures were parameterized (see Figs. 1 and 2). The spectral parameters are the amplitude of the first peak (or minimum) $A^I$ and the peak height $H^I$. The signal amplitude is defined by the overall electric fields distribution in the structure, which is dictated by $\delta_{\text{top}}$, $\delta_{\text{bot}}$, and $Q_{\text{sur}}$. Thus, $A^I$ depends on all charges densities in the structure. $H^I$ is a result of the strong interplay between the PV from the Schottky and buffer layers. This interplay depends on the electric field distribution in the buffer and Schottky layers, which is defined by $\delta_{\text{top}}$ and $\delta_{\text{bot}}$.

The empirical model, which correlates between the spectral features $A^I$, $H^I$ and the structural parameters $\delta_{\text{top}}$, $\delta_{\text{bot}}$, and $Q_{\text{sur}}$ has been developed using numerical simulations. This model has been applied to several PHEMT structures and the efficiency of the model for PHEMT characterization is shown in Ref. 15. $\delta_{\text{top}}$, $\delta_{\text{bot}}$, and $Q_{\text{sur}}$ are changed in the simulated structures and their effects on $A^I$ and $H^I$ from simulated spectra have been analyzed. A two-level factorial design has been used to define the device structure with different combinations of structural parameters.

Figure 1 shows parts of SPV spectra of a double-sided delta-doped PHEMT structure (solid curve) and two MHEMT structures, $M_1$ (circles) and $M_2$ (squares). Inset: Simulated SPV signal from a double-sided delta-doped PHEMT structure (solid curve) together with simulated signals from buffer (circles) and Schottky layer (squares).
coefficients are given in Ref. 15. The model shows that the differences in a spectral parameter $A'$ (relative to a reference structure) is given by

$$\Delta A'(\delta_{\text{top}}, \delta_{\text{bot}}, Q_{\text{sur}}) = C_{\delta_{\text{top}}} \Delta \delta_{\text{top}} + C_{\delta_{\text{bot}}} \Delta \delta_{\text{bot}} + C_{Q_{\text{sur}}} \Delta Q_{\text{sur}},$$

(1)

where $C_{\delta_{\text{top}}}, C_{\delta_{\text{bot}}}, C_{Q_{\text{sur}}}$ are coefficients, which weight the influence of each of the electrical parameters on the spectral parameter $A'$. Here we present the capability of the model to characterize HEMT structures with different material composition and to predict final device performance.

Spectra of double-sided delta-doped HEMT (represented by the solid curve in Fig. 1) and MHEMT (dotted curve) were compared. The $\delta_{\text{top}}$ in the PHEMT structure is $5 \times 10^{12}$ cm$^{-2}$. The structures have the same $\delta_{\text{bot}}$ level and the difference in $\delta_{\text{top}}$ specified by the supplier is $1 \times 10^{12}$ cm$^{-2}$. Variations in $\delta_{\text{top}}$ change the electric field distribution in the Schottky layer region and thus the spectral shapes of the QW absorption region significantly differ. The difference in $\delta_{\text{top}}$ has been calculated using the model. $Q_{\text{sur}}$ is assumed to be the same, which reduces Eq. (1) to $\Delta A' = 130 \Delta \delta_{\text{top}}$. The calculated $\Delta \delta_{\text{top}}$ is $0.9 \times 10^{12}$ cm$^{-2}$, which is in good agreement with the grower specifications. Two single-sided top-delta-doping structures of GaN/AlGaN HEMT and MHEMT have been compared using the empirical model. In these HEMTs, $\delta_{\text{top}} = 1.0 \times 10^{13}$ cm$^{-2}$ and $0.6 \times 10^{13}$ cm$^{-2}$, respectively. The value of $\Delta \delta_{\text{top}}$ calculated from the model is $4.4 \times 10^{12}$ cm$^{-2}$, which is in good agreement with the supplier specifications.

Therefore, the model developed for double-sided delta-doped PHEMT structures accounts well for differences in $\delta_{\text{top}}$ of GaN HEMT and MHEMT structures. This model is applicable for double-sided delta-doped as well as for single-sided delta-doped structures. It shows that this is a universal empirical model, sensitive to differences in doping levels for a wide variety of HEMT structures.

Demonstrating the capability of this methodology to predict the final device performance, two MHEMT structures have been characterized by SPS and consequently complete devices have been fabricated on the substrates. The differences in delta-doping levels indicate variations in the channel sheet density $n_s$, where $n_s$ defines a maximum current $I_{\text{max}}$ for a given device. Therefore, by monitoring differences in the delta-doping levels, difference in the final device performance may be predicted.

The model has been applied to the two double-sided delta-doped MHEMT structures, $M1$ and $M2$, whose spectra are shown by the circles and squares, respectively in Fig. 1. The $\delta_{\text{bot}}$ is the same for both structures while $\delta_{\text{top}}$ as given by the grower is $0.5 \times 10^{12}$ cm$^{-2}$. The value calculated from the model is $\Delta \delta_{\text{top}} = 0.3 \times 10^{12}$ cm$^{-2}$, which corresponds to a relative change of 7.5%. Devices produced on $M1$ and $M2$ structures have been characterized. A relative difference of 8.2% in $I_{\text{max}}$ was measured correlating with the difference in $\delta_{\text{top}}$ extracted from the model. This demonstrates the sensitivity of our methodology to even slight differences in the delta-doping level, allows prediction of the device dc and power performance.

In conclusion, GaN/AlGaN HEMT, MHEMT, and PHEMT epitaxial structures have been characterized by SPS. Effects of $\delta_{\text{top}}$, $\delta_{\text{bot}}$, and $Q_{\text{sur}}$ on SPV spectra were found, using numerical simulations. A complete empirical model providing doping levels has been developed. The universality of the model for characterization of HEMT structures of various material compositions is shown. The capability of characterization using SPS to predict the final device performance has been demonstrated for MHEMT structures.

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