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Investigation of generation-recombination centres of Au/n-GaAs Schottky diodes with InAs self-assembled quantum dots

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ABSTRACT

Capacitance and reverse current–voltage measurements have been performed as a function of temperature on Au/n-GaAs Schottky diodes with InAs quantum dots (QDs) embedded between two GaAs spacers. The spacers were either doped or undoped containing a QD layer equivalent to 3 monolayer (ML) QD coverage. In the investigated temperature range of 77–350 K and for all the diodes measured, the apparent free electron concentration close to the QDs layer is lower compared to the concentration at the interface between GaAs doped buffer layer and GaAs n^+-substrate, showing that the QDs induce more traps than those created at a conventional interface. Theoretical fitting of the capacitance–voltage characteristics yields the values of the energy level, the sheet concentration and the dispersion of the distribution of the confined states induced by the InAs quantum dots, which is higher for the diode with doped GaAs spacers than for the diode with undoped spacers. The effective activation energies of the traps, obtained from the effective generation lifetime calculated from reverse voltage current, agree well with the results obtained from the theoretical fitting.

1. Introduction

Self-assembled InAs quantum dots (QDs), embedded in a GaAs layer, have attracted major interest in the recent years due to their applications in the QD lasers, light-emitting diodes, photodetectors, and quantum transistors [1–4]. For these devices, electron emission and capture processes from the QDs are the main considerations, resulting in peculiar characteristics. Many techniques have been used for fabricating three-dimensional quantum dots, metal-organic chemical-vapor deposition, molecular beam epitaxy (MBE), and atomic layer MBE (ALMBE). For the growth of rather homogeneous ensembles of the three-dimensional self-assembled QDs, the most successful deposition technique is the Stranski-Krastanov growth mode [5,6]. The electronic properties of the QDs and especially the role of the electron emission from QDs lead to the need for further investigation of the QDs induced traps. Generation-recombination centres are responsible for emission and capture processes affecting the leakage current and the capacitance measured in reverse bias. In addition, the leakage current flowing through structures comprising QDs is a key factor in determining the device performance.

In the present work, we investigate the doping effect on the generation-recombination centres of Au/n-GaAs Schottky diodes with embedded QDs, using reverse current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) measurements in the temperature range of 77–350 K. Furthermore, we used a simple theoretical model to fit the *C*–*V* experimental data in order to find the sheet concentration and the energy position of the confined states in the energy gap of GaAs.

2. Experimental

First, GaAs buffer layers with an electron concentration of $2 \times 10^{16}\,\mathrm{cm^{-3}}$ (1 μm thick) were grown on n^+-GaAs substrates by MBE at 580 °C. Then, a spacer of GaAs (10 nm thick) was grown by MBE, and an equivalent coverage of three monolayers of InAs was deposited by ALMBE at 460 °C followed by the deposition of another spacer of GaAs. The spacers of GaAs are either undoped or doped with the same electron concentration as the buffer layer ($2 \times 10^{16}\,\mathrm{cm^{-3}}$). At last, an upper GaAs-confining layer with an electron concentration of $2 \times 10^{16}\,\mathrm{cm^{-3}}$ and thickness of 0.8 μm was grown by MBE at 400 °C. Atomic force microscopy analysis has shown that the density of the QDs is in the order of $10^{11}\,\mathrm{cm^{-2}}$ [7]. The details of the growth procedures are presented elsewhere [8].

For current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) measurements, Schottky diodes were fabricated on the mentioned

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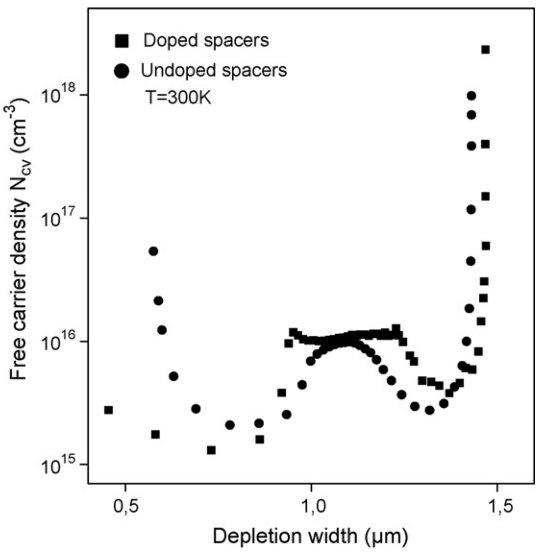

Fig. 1. Free carrier concentration as a function of the depletion region width at room temperature.

samples by evaporating Au circular dots with a diameter of 400 μm using a conventional photolithographic technique. The backside ohmic contact was formed by evaporation and annealing of the AuGeNi alloy. For the electrical characterization of the Schottky diodes, *I*–*V* measurements were performed as a function of temperature in the temperature range of 77–350 K using a computer-controlled system including a Keithley 617 electrometer and Keithley 230 voltage source. The *C*–*V* characteristics were measured using a Boonton capacitance meter at the frequency of 1 MHz. Theoretical fitting of the capacitance–voltage characteristics was performed by numerical calculations using Mathcad.

3. Results and discussion

Fig. 1 shows the apparent free electron doping concentration as a function of the width of the space charge region for the diodes with doped and undoped spacers measured at room temperature. The free electron doping concentration and the space charge region width are calculated from the equations:

$$N_{\rm free} = -\frac{C^3}{qA^2\varepsilon({\rm d}C/{\rm d}V)}, \quad W = \frac{\varepsilon A}{C} \tag{1}$$

where A is diode area and ε is the dielectric constant of GaAs. Fig. 1 shows that there are two minima correlated with two distinct trap regions created above the InAs QDs layer and between the GaAs buffer layer and the substrate with the former being wider in space than the latter one. The free electron concentration is lower in the space charge region above the QD layer than in the space charge region between the GaAs buffer layer and the substrate, which indicates that the QDs growth induces more traps in the GaAs capping layer broadening the space charge region owned to them.

Fig. 2 shows the *C*–*V* characteristics for the diodes with doped and undoped spacers measured at 350 K. For a homogeneous Schottky diode, the capacitance should decrease monotonically as the width of the space charge region increased. Both characteristics reveal two peaks corresponding to the trap regions above the QDs and below them. These two peaks are related to the presence of generation-recombination centres that are able to follow the small AC signal of the Boonton capacitance meter at 1 MHz [10].

The relation used to obtain the bulk GaAs contribution to the total capacitance is given by the classical equation:

$$C_{\rm bulk} = A\sqrt{\frac{2\varepsilon}{qN_{\rm D}}\left(V_{\rm bi} - V - \frac{kT}{q}\right)} \tag{2}$$

where $N_{\rm D}$ is the donor concentration, ε the dielectric constant of the GaAs, $V_{\rm bi}$ the built-in voltage and V the voltage applied to the diode. The other symbols have their usual meanings. The AC measurement signal modulates the charge at the edge of the space charge region formed by the Schottky barrier, which is extended as the reverse voltage is increased. If a deep trap distribution exists in the energy gap of GaAs, the Fermi level intersects the energy level of the trap and the total capacitance increases as a result of the electron depopulation of the trap energy level. The same behaviour appears as well in the case when the depletion layer width reaches the quantum dot layer and the Fermi level intersects the trap energy level in the InAs quantum dot energy gap. The theoretical fit of the capacitance–voltage characteristics is obtained using the equation:

$$C_{\rm total} = C_{\rm bulk} + C_{\rm trap} + C_{\rm dot} \tag{3}$$

where C_{trap} is the capacitance contribution of a deep trap distribution at the GaAs buffer layer and $C_{\rm dot}$ is the capacitance contribution of the quantum dots layer. Both trap distributions are assumed to be of the form given below. $C_{\rm dot}$ is given by the equation [9]:

$$C_{\rm dot} = qAL\frac{\partial}{\partial V_{\rm dot}}\int D_i(E, V_{\rm dot})xf(E, V_{\rm dot}) \tag{4}$$

where $D_i(E, V_{\rm dot})$ is the density of states and $f(E, V_{\rm dot})$ is the Fermi–Dirac energy distribution. The density of states in the quantum dot layer could be described by a distribution reflecting the non-uniform distribution in size of the quantum dots and is given by the equation:

$$D_{\rm i}(E, V_{\rm dot}) = \frac{g_{\rm i}N_{\rm dot}}{\sqrt{\pi/2\Delta E}}\exp\left[-2\left(\frac{E + E_{\rm i} + qV_{\rm dot}}{\Delta E_{\rm i}}\right)^2\right] \tag{5}$$

where the Fermi–Dirac energy distribution function is given by the equation:

$$f(E, V_{\rm dot}) = \frac{1}{1 + \exp(E - qV_{\rm dot}/kT)} \tag{6}$$

In Eqs. (5) and (6), $g_{\rm i}$ is the spin degeneracy, $E_{\rm i}$ is the confined energy level in the InAs quantum dots energy gap with respect to the GaAs conduction band edge, $\Delta E_{\rm i}$ is the energy dispersion of the quantum dot density of states, $N_{\rm dot}$ is the total number of traps

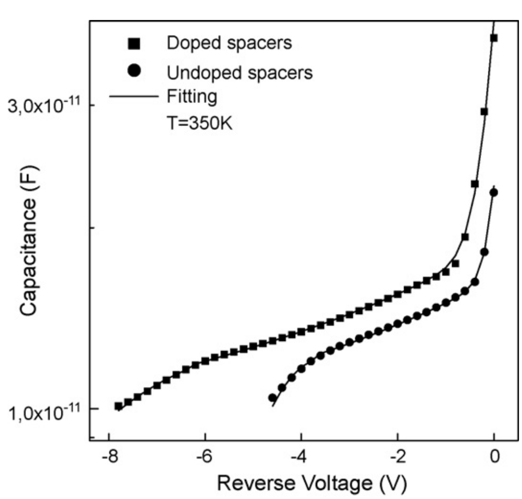

Fig. 2. Capacitance–voltage characteristics for the diodes with doped and undoped spacers measured at a typical temperature of 350 K.

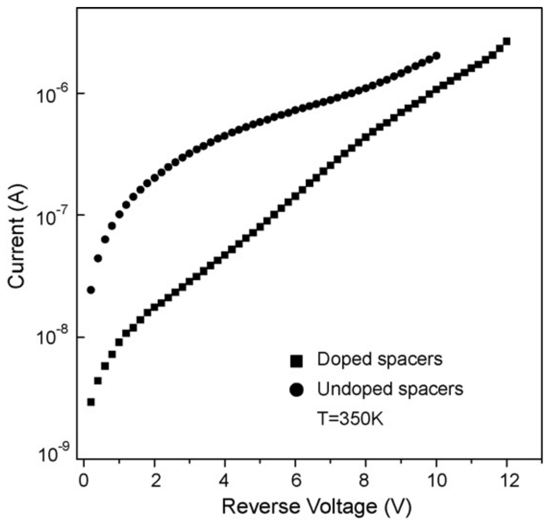

Fig. 3. Current as a function of reverse voltage characteristics for the diodes with doped and undoped spacers measured at a typical temperature of 350 K.

corresponds to the total number of quantum dots, V_{dot} is the voltage drop across the quantum dots and L is the level arm coefficient. The level arm coefficient equals d/t where d is the thickness of the capping layer and t is the total sample thickness. For the samples used in this work the level arm coefficient is 4/9.

Eq. (4) has been numerically solved. The fitting of the C–V characteristics for both samples were obtained as the summation of the bulk capacitance predicted by the Eq. (2) and the capacitance due to the two trap distributions related with the QDs. The traps induced due to the presence of the QDs have an energy dispersion $\Delta E = 120$ meV for the diode with doped spacers and $\Delta E = 100$ meV for the diode with the undoped spacers. The fact that the energy dispersion of the traps induced by the QDs in the diode with doped spacers is greater than the energy dispersion in the diode with the undoped spacers show that the spacers doping affects also the size dispersion of the QDs probably due to different mechanical stress induced by the GaAs spacers. Moreover, the sheet concentration of traps for the diode with doped spacers is $N_{dot} = 3.6 \times 10^{11}$ cm^{-2} which is higher than $N_{dot} = 1.4 \times 10^{11}$ cm^{-2} for the diode with the undoped spacers. The higher sheet concentration of traps induced by the QDs for the diode with doped spacers agrees qualitatively with the lower apparent free electron concentration for the same sample presented in Fig. 1. Furthermore, the values of the sheet concentration of traps are of the same order of the QDs density calculated from AFM measurements [7], corresponding approximately to one trap per dot as found in a previous work [10]. The energy position of the trap states is 110 meV below the GaAs conduction band edge for the diode with doped spacers and 130 meV below the GaAs conduction band edge for the diode with undoped spacers.

The fitting for the second deep trap energy distribution, located at the interface between the GaAs buffer layer and the substrate, yields almost the same values for the density of traps $N = 3.0 \times 10^{11}$ cm^{-2} while the energy dispersion is $\Delta E = 260$ meV for both samples. The energy position of the trap state is 0.68 eV below the GaAs conduction band edge for diode with doped spacers and 0.43 eV for the diode with undoped spacers.

Fig. 3 shows the reverse current–voltage characteristics measured at 350 K as a function of reverse voltage for the diodes with doped and undoped spacers. It is well known that the reverse current is affected by the generation-recombination conduction mechanism. Theory predicts that the reverse generation-recombination current should be a linear function of W [11]:

$$J_{\text{generation}} \approx q\frac{n_i}{\tau_g}W \tag{7}$$

where τ_g is the generation lifetime and n_i is the intrinsic carrier density. Fig. 3 clearly shows that there is an excess current in the voltage region from −0.4 to −4 V, where the space charge region width reaches the position of the QDs layer and the deep trap density close to the interface between GaAs capping layer and GaAs n$^+$-substrate.

According to the model of Murakami and Shingyouji [11], the generation lifetime can be obtained by the relation:

$$\tau_g = qn_i\varepsilon_s\varepsilon_0\frac{d(1/C)/dV}{d(J_g)/dV} \tag{8}$$

In our case, the generation lifetime is an effective generation lifetime corresponding to traps induced by the QDs in the GaAs capping layer and to traps lying in the GaAs buffer layer. Clearly, the effective generation lifetime is controlled by the confined states induced by the QDs layer for the case of the traps lying in the GaAs capping layer. The effective generation lifetime, corresponding to the traps in the GaAs buffer layer, depends on the quality of the interface between the buffer layer and the substrate. Fig. 4 shows the effective generation lifetime as a function of the square root of the electric field for both samples at the temperature of 350 K. The maximum presented for the lower values of electric fields corresponds to the traps induced by the QDs and the maximum presented for the higher values of electric field corresponds to the traps in the GaAs buffer layer.

Arrhenious plots of the effective generation lifetime, calculated with Eq. (8), are shown in Fig. 5(a) and (b) for the diode with doped and undoped spacers, respectively. The effective activation energy, corresponding to the traps induced by the QDs, is the same for the two samples correlated with the energy required for the electrons to be excited from the confined energy states to the GaAs conduction band edge. The activation energy for the confined states, located at the GaAs capping layer, is the same for the two samples meaning that the doping does not affect the position of the trap in the GaAs energy gap. The effective activation energies calculated for the second trap distribution are 0.64 eV for the diode with doped spacers and 0.34 eV for the diode with undoped spacers. These values are close to the values obtained from the fitting of

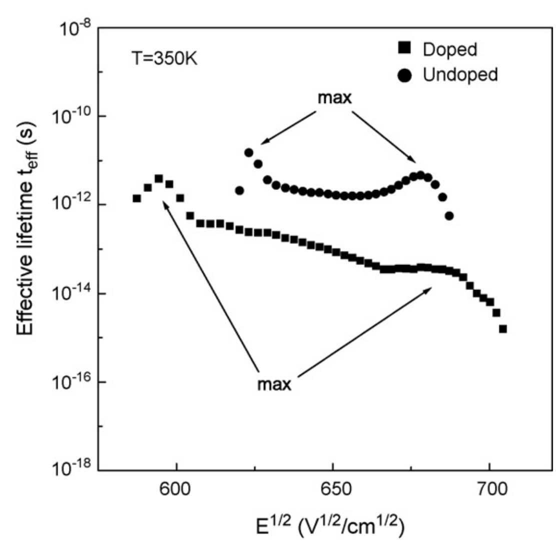

Fig. 4. Effective generation lifetime as a function of the square root of the electric field for the diodes with doped and undoped spacers calculated at a typical temperature of 350 K.

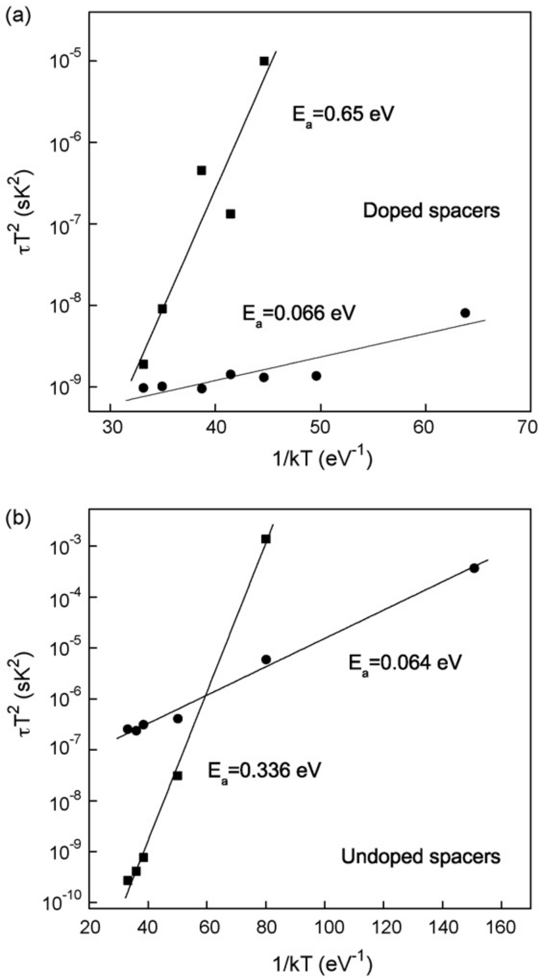

Fig. 5. Arrhenious plots for the diodes with doped (a) and undoped (b) spacers for the trap located at the capping layer of GaAs (circles) and the trap located at the buffer layer of GaAs (squares).

the *C–V* characteristics for both samples showing that the doping of the spacers affects the energy position of the trap located in the GaAs buffer layer.

4. Conclusions

The effect of the spacer doping in Au/n-GaAs Schottky diodes with embedded InAs quantum dots was investigated by *I–V* and *C–V* measurements in the reverse voltage regime. The apparent free electron density shows that there are two trap distributions in the capping and buffer layers of GaAs. The trap distribution located in the capping layer of GaAs has a higher concentration and is wider in space than the trap distribution located in the GaAs buffer layer. Theoretical fitting of the *C–V* characteristics show that the energy level of confined states, induced by the QDs in the capping layer of GaAs, is affected as well as the sheet concentration and the energy dispersion by the spacer doping. This can be attributed to the different size dispersion of the QDs. The effective activation energy, calculated from the reverse current–voltage characteristics, shows the same activation energy for the confined states in the capping GaAs layer while the activation energy of the trap located in the buffer layer of GaAs is higher for the diode with doped spacers.

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