Stress-Induced Local Trap Levels in Au/n-GaAs Schottky Diodes With Embedded InAs Quantum Dots

A. Tsormpatzoglou, D. H. Tassis, C. A. Dimitriadis, *Member, IEEE*, P. Frigeri, S. Franchi, E. Gombia, and R. Mosca

Abstract—Local trap levels in Au/n-GaAs Schottky diodes with embedded InAs quantum dots, generated after a long time of the device operation, have been investigated with low-frequency noise measurements performed in the temperature range of 77–298 K and at the forward current of 30 nA. Whereas the initial devices show a pure $1/f$ noise behavior, after a long time of operation, recombination noise was observed at frequencies above 100 Hz, in addition to the $1/f$ noise at lower frequencies. Analysis of the recombination noise data obtained on structures where different GaAs cap layer thicknesses have been removed by etching allowed us to determine the activation energy of the local traps and have a rough estimation of their spatial distribution.

Index Terms—InAs quantum dots (QDs), noise, stress, traps.

I. INTRODUCTION

InAs quantum dots (QDs) embedded in GaAs layer have been extensively studied in the previous years due to their applications in lasers, light-emitting diodes, and photodetectors [1]. The luminescence efficiency of these devices depends on the electronic properties of the QD structures and especially on the QD-induced traps in the confining GaAs layers. Capacitance and deep-level transient spectroscopy techniques have been widely used to characterize such traps [2]–[5]. Recently, low-frequency noise (LFN) measurements were performed at room temperature to characterize the electronic properties of the InAs QDs embedded in GaAs layer [6]. Furthermore, it has been demonstrated that the electrical characteristic of the diode changes dramatically under current injection, due to high local current densities at the QDs [7]. The capacitance–voltage characteristics exhibited hysteresis after current stress, explained by a generation of point defects and/or dislocations [7]. Therefore, reliability issues in QDs are important and may play a significant role on the stability of the QD luminescence efficiency. In this letter, local trap levels in Au/n-GaAs Schottky diodes containing InAs QDs are investigated after a long time of the device operation. The temperature dependence of noise provides valuable information about stress-induced single-energy traps in the GaAs confining layers.

II. EXPERIMENTAL

The investigated samples were grown on n+-GaAs substrates by molecular beam epitaxy (MBE) and atomic layer MBE (ALMBE). First, GaAs buffer layers with electron concentration of 2 x 10^{16} cm^{-3} (1 μm thick) were grown on n$^+$-GaAs substrates by MBE at the temperature of 580 °C. Then, a spacer of undoped GaAs (10 nm thick) was grown by MBE, and 2.4 monolayers (ML) coverage of InAs was deposited by ALMBE at the temperature of 460 °C, followed by deposition of another 10-nm-thick spacer of undoped GaAs. According to the Stranski–Krasanov growth mode, self-aggregated threedimensional InAs QDs were formed with mean lateral size of ~19 nm and a density of the order of 10^{11} cm^{-2} [8]. Finally, an upper GaAs confining layer with electron concentration of about 2 x 10^{16} cm^{-3} and thickness of 0.8 μm was grown by MBE at the temperature of 580 °C. To determine the depth distribution of the stress-induced traps, the thickness of the upper GaAs confining layer was reduced using a solution of H_3PO_4-H_2O_2-H_2O. Schottky diodes were formed by evaporating circular dots of Au 400 μm in diameter, and the backside ohmic contact was formed by evaporation and annealing of AuGeNi alloy. The thicknesses of the upper GaAs confining layers was 0.8, 0.52, and 0.24 μm, and the corresponding Schottky diodes are defined as D1–D3, respectively.

In all diodes, current–voltage (*I–V*) measurements were performed at room temperature using a computer-controlled system. For performing noise measurements, the diode was loaded in a liquid nitrogen cryostat, and the temperature of the sample was varied from about 77 to 298 K using a temperature controller. The temperature was stable within 0.1 K at each temperature value. The spectral power density S_I of the current fluctuation was measured at the forward current of 30 nA and for different temperatures using an SR760 spectrum analyzer, where a low-noise *I–V* converter and a low-noise voltage amplifier previously amplified the current. The bias voltage was supplied from CdNi batteries to avoid any external noise.

III. RESULTS AND DISCUSSION

The room-temperature forward I_F −V_F characteristics of typical as-fabricated Au/n-GaAs Schottky diodes D1–D3 are presented in Fig. 1. These plots show linearity over six decades of current magnitude, without the QDs affecting seriously the electrical behavior of the diodes. However, after performing a series of *I–V* measurements in the voltage range from -12 to 1.5 V at different temperatures, the room temperature characteristics are degraded as shown in Fig. 1. For each *I–V* characteristic, delayed measurements (up to 5 s between each point and up to 5 min for each sweep) and averaging were used to avoid noise in the current region below 1 nA. These diodes with the degraded characteristics will be referred below as stressed diodes. The forward current in the high-voltage region remains almost unchanged, whereas an excess current in the low-voltage region is observed, indicating recombination conduction mechanism due to stress-induced traps in the depletion region of the Schottky contact. Inasmuch as the excess current appears to be higher in the diode with the thinner GaAs cap layer, a larger number of traps could be created near the QDs.
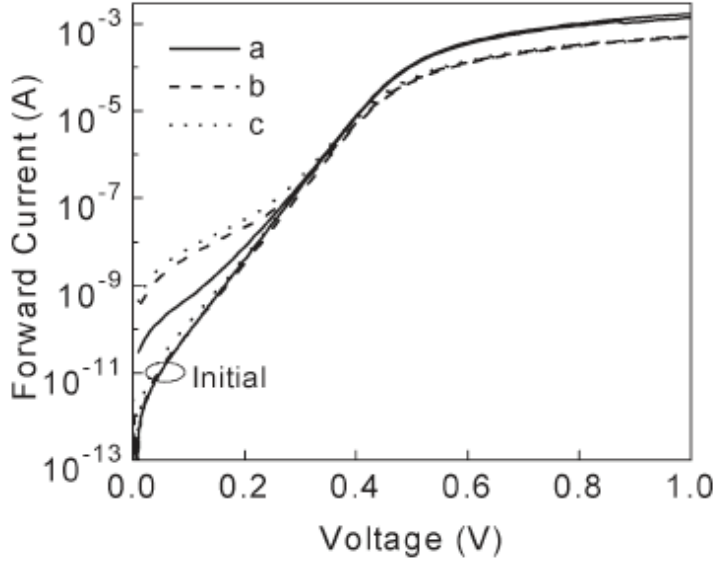
Fig. 1. Forward *I–V* characteristics of as-fabricated Au/n-GaAs Schottky diodes containing InAs QDs, measured at room temperature. GaAs cap layer thickness: (a) 0.8 _m, (b) 0.52 _m, and (c) 0.24 _m. Degraded *I–V* characteristics of the stressed diodes are also presented.

LFN measurements in forward-biased Schottky diodes can provide information about the recombination centers. Noise measurements in the as-fabricated diodes have shown that the noise spectra are composed of a $1/f$ noise at frequencies below 100 Hz attributed to the interface trap property and a shot noise at higher frequencies [6]. The absence of recombination noise indicated that the quality of the as-grown GaAs confining layers remains unchanged after the growth of InAs QDs with an equivalent thickness of 2.4 ML [6]. Fig. 2(a) shows the typical noise spectrum measured at the forward current of 30 nA and temperature of 146 K for the stressed Schottky diode D1. At frequencies lower than 100 Hz, the spectrum shows $1/f$ frequency dependence, whereas at higher frequencies, the spectrum tends to form a plateau, followed by $1/f2$ dependence. The last behavior is attributed to recombination noise, indicating the presence of single-energy trap in the bulk of the GaAs capping layer. The $1/f$ and *i*-number uncorrelated recombination noise components were separated using the relation

$$S_I = \frac{A}{f} + \sum_{i=1}^{m} \frac{\frac{B_i}{f_{ci}}}{1 + \left(\frac{f}{f_{ci}}\right)^2} \tag{1}$$

where *A* and *B* are fitting constants and f_{ci} are the corner frequencies of the recombination centers. Fig. 2(a) shows the decomposition of a measured spectrum to $1/f$ and recombination noise components.
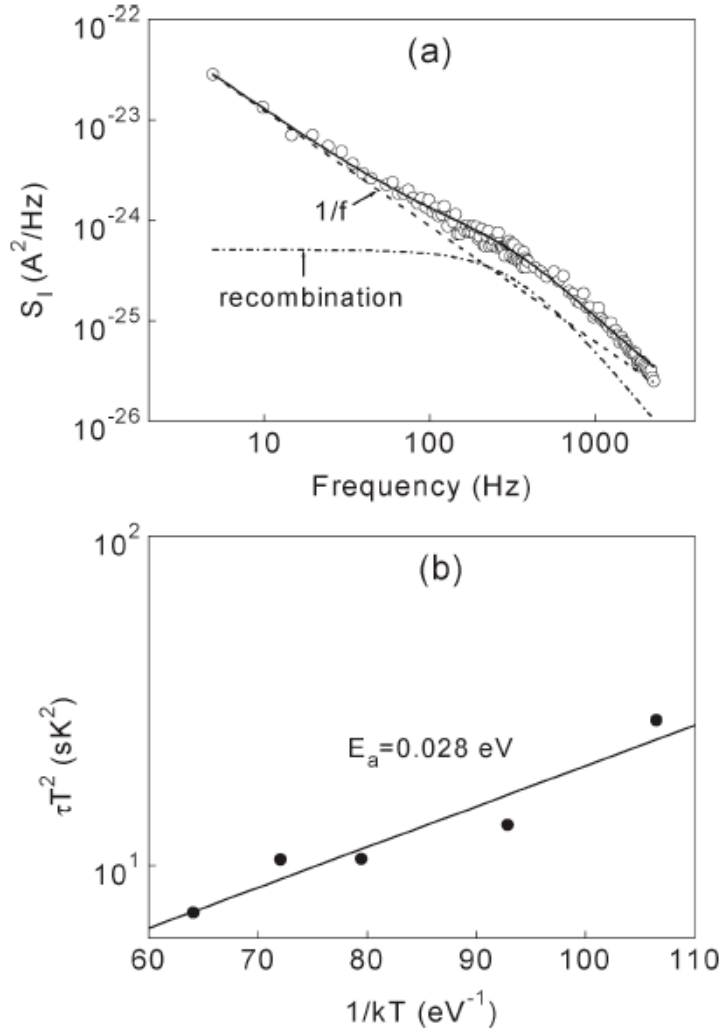
Fig. 2. (a) Decomposition into 1/*f* and recombination components of a typical noise spectrum, measured at 146 K and forward current of 30 nA in stressed Au/n-GaAs Schottky diode D2 containing InAs QDs, with GaAs cap layer of thickness 0.8 μm. (b) Arrhenius plot of τ/T^2 versus $1/T$, obtained from analysis of the measured noise spectra at different temperatures.

Each recombination noise component is associated with a local trap level with a time constant _ related to the corner frequency fc of the Lorentzian spectrum by the relation $f_c = 1/2\pi\tau$. The corner frequency f_c at each temperature was determined by fitting the experimental noise spectrum with (1). However, the time constant of each trap level follows the Arrhenius equation $\tau = \tau_0 \exp(E_a/kT)$, where kT is the thermal energy, E_a is the activation energy of the trap level, and τ_0 is a constant proportional to T^{-2} [9]. Thus, the Arrhenius plot of $\log(\tau T^2)$ versus 1/T must give a straight line from the slope of which the activation energy of the trap level can be determined as shown in Fig. 2(b) for the diode D1. From this figure, in the considered frequency and temperature ranges, it has been found that a trap level with activation energy Ea = 28 meV contributes to the LFN of the stressed diode D1.

For the stressed diode D2, two noise components were observed, i.e., 1) 1/f noise at frequencies below 100 Hz and 2) a recombination noise at higher frequencies. Fig. 3

shows the Arrhenius plot of log(τT2) versus 1/T , derived from analysis of the noise spectra of the stressed diode D2, which was measured for the forward current of 30 nA at different temperatures. Besides the trap with activation energy $E_{a1} = 28$ meV, which is common in both D1 and D2, two additional deeper traps (i.e., $E_{a2} = 48$ meV and $E_{a3} = 109$ meV) contribute to the noise in diode D2.
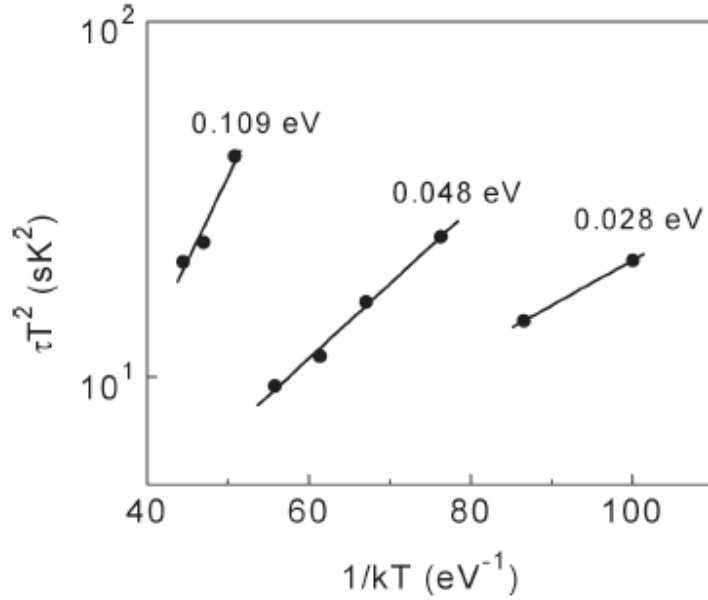

Fig. 3. Arrhenius plot of log(_T2) versus 1/T , derived from analysis of the noise spectra of the stressed Schottky diode D2 containing InAs QDs at a distance of 0.52 μm from the interface. The spectra were measured at the forward current of 30 nA for different temperatures.
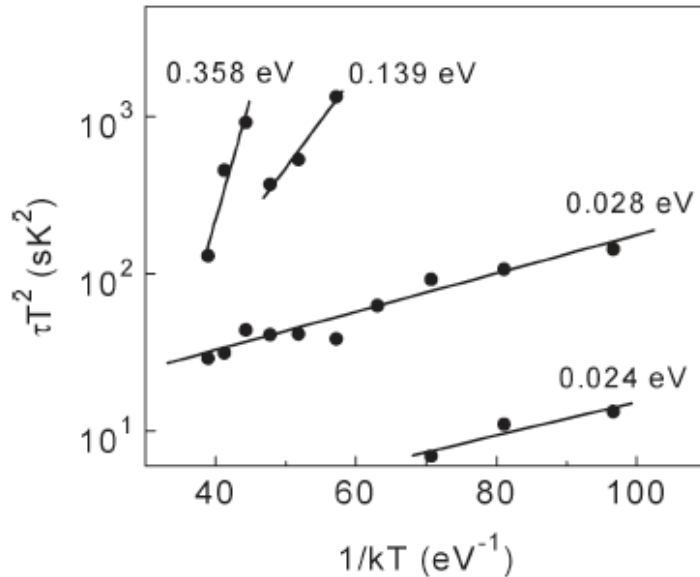

Fig. 4. Arrhenius plot of log(_T2) versus 1/T , derived from analysis of the noise spectra of the stressed Schottky diode D3 containing InAs QDs at a distance of 0.24 μm from the interface. Spectra were measured at the forward current of 30 nA for different temperatures.

For the stressed diode D3, two recombination noise components were observed in the

investigated frequency and temperature regions. Fig. 4 shows the Arrhenius plot of log($\tau T2$) versus 1/T , derived from analysis of the noise spectra of the stressed Schottky diode D3, which was measured for the forward current of 30 nA at different temperatures. In addition to the trap with activation energy E_{a2}=28 meV, which is common in all diodes, a shallow trap (i.e., E_{a1} = 24 meV) and two deeper traps (i.e., E_{a3}=139 meV and E_{a4}=358 meV) contribute to the noise in diode D3. Inasmuch as the space charge region of the contact at the forward current of 30 nA is about 0.2 μm, the detected traps are located close to the QD plane The aforementioned findings indicate that thinner GaAs cap layers are more prone to stress-induced degradation. The size of the QDs and the number of the inserted QD layers are expected to affect the device stability under current stress conditions, and this will be the subject of our future work.

IV. CONCLUSION

The forward I_F–V_F characteristics of as-fabricated Au/n-GaAs Schottky diodes containing InAs QDs are degraded after a long time of operation. Local trap levels were investigated by LFN measurements performed at the forward current of 30 nA in the temperature range of 77–298 K. Analysis of the observed recombination noise shows that more localized trap levels are created in thinner GaAs cap layer.

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