ФІЗИЧНІ, ХІМІЧНІ ТА ІНШІ ЯВИЩА, НА ОСНОВІ ЯКИХ МОЖУТЬ БУТИ СТВОРЕНІ СЕНСОРИ

PHYSICAL, CHEMICAL AND OTHER PHENOMENA, AS THE BASES OF SENSORS

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INVESTIGATION OF NEGATIVE DIFFERENTIAL CAPACITANCE-VOLTAGE DEPENDENCES OF SHOTTKY DIODE STRUCTURES WITH GAAS/INAS QDS

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Summary

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Capacitance-voltage investigations were made on Schottky diodes with embedded GaAs/InAs quantum dots and quantum wells. An effect of the negative differential capacitance(NDC) was clear observed. Numerical modeling of the C-V dependences was carried out with temperature and concentration of QDs as parameters. Energy structure of the investigated samples was examined by deep level transient spectroscopy(DLTS). It was shown that the proposed model is in good agreement with experiment and describes well the NDC effect.

Key-Words: Quantum dot, quantum well, negative differential capacitance, DLTS.

Анотація

ДОСЛІДЖЕННЯ ВОЛЬТ-ФАРАДНИХ ЗАЛЕЖНОСТЕЙ, ЩО МАЮТЬ НЕГАТИВНУ ДИФЕРЕНЦІАЛЬНУ ЄМНІСТЬ, ДІОДІВ ШОТТКІ З GAAS/INAS КВАНТОВИМИ ТОЧКАМИ

С. Д. Лін, С. П. Лі, В. В. Ільченко, В. В. Марін, М. В. Шкіль, А. А. Буянін, К. Ю. Панарін, О. В. Третяк

Вольт-фарадні дослідження проводилися на діодах Шотткі з GaAs/InAs квантовими точками та квантовими ямами. Експериментально спостерігався ефект негативної диференціальної ємності(НДЄ). Енергетична картина структур досліджувалася за допомогою релаксаційної спектроскопії глибоких рівнів. Було проведено чисельне моделювання вольт-фарадних залежностей, де параметрами були температура та концентрація квантових точок, що описує ефект НДЄ та добре співпадає з експериментальними результатами.

Ключові слова: Квантова точка, квантова яма, негативна диференціальна ємність, РСГР.

Аннотация

ИССЛЕДОВАНИЕ ВОЛЬТ-ФАРАДНЫХ ЗАВИСИМОСТЕЙ С НЕГАТИВНОЙ ДИФФЕРЕНЦИАЛЬНОЙ ЕМКОСТЬЮ ДИОДОВ ШОТТКИ С GAAS/INAS КВАНТОВЫМИ ТОЧКАМИ

С. Д. Лин, С. П. Ли, В. В. Ильченко, В. В. Марин, Н. В. Шкиль, А. А. Буянин, К. Ю. Панарин, О. В. Третяк

Вольт-фарадные исследования проводились на диодах Шоттки с GaAs/InAs квантовыми точками и квантовыми ямами. На экспериментальных зависимостях наблюдался эффект негативной дифференциальной емкости(НДЕ). Энергетическая картина структур исследовалась с помощью релаксационной спектроскопии глубоких уровней. Было проведено численное моделирование вольт-фарадных зависимостей, которое описывает эффект НДЕ и хорошо совпадает с экспериментальными результатами.

Ключевые слова: Квантовая точка, квантовая яма, негативная дифференциальная емкость, РСГУ.

I. Introduction

Last years the investigation of structures with self-assembled quantum dots (QDs) draws the increasing attention of scientists and technologists because of the prospect of the creation of functionally new devices of nanoelectronics. Because of the new abilities to accumulate the carriers of a charge in the QDs which could built into various semiconductor heterojunctions such structures are capable to show the certain physical phenomenon connected with charge of QDs and reveal some specific features in capacitance-voltage (C-V) dependences[1-6]. Authors of main part of papers present experimental results of the investigation of the C-V dependences for structures with QDs layers and determination such parameters of QDs, as concentration, energetic position and capture cross-section. They discussed considerably widespread peculiarities of C-V dependences of the Schottky structures with well-known "shelf" in such dependences connected with charge accumulation in QDs states[3-6]. A number of authors proposed some methods for the detail calculation of the capacitance and compared experimental and theoretical results[7-9]. At the same time all of them considered only cases when quantity of QDs states where charge accumulated was not enough to be comparable or even locally overcompensated the charge of main part of the spatial charge region (SCR). Although, it should be noted that at high enough density of QDs in multi-layer structures negative charge accumulated in ground and excited states of QDs can cause some unusual properties of these structures and reveals specific behavior of C-V dependences with negative differential capacitance (NDC) due to unique redistribution of charge in the SCR.

II. Samples and experiments results

The purpose of the present work is to investigate influence of QDs on the C-V characteristics of the Shottki diode obtained on the basis of GaAs matrix with multi-layers of InAs QDs (with high density of states) and layers combined of quantum wells(QWs) and QDs layers placed in the middle of QWs built into the SCR of the diode. Both of these cases show unusual capacitance dependences containing a part with the NDC on the C-V curve. The investigated structures were prepared by the molecular-beam epitaxy(MBE) method using Varian GEN II system.

Detailed scheme of the structures investigated in the present work are shown on Fig. 1.

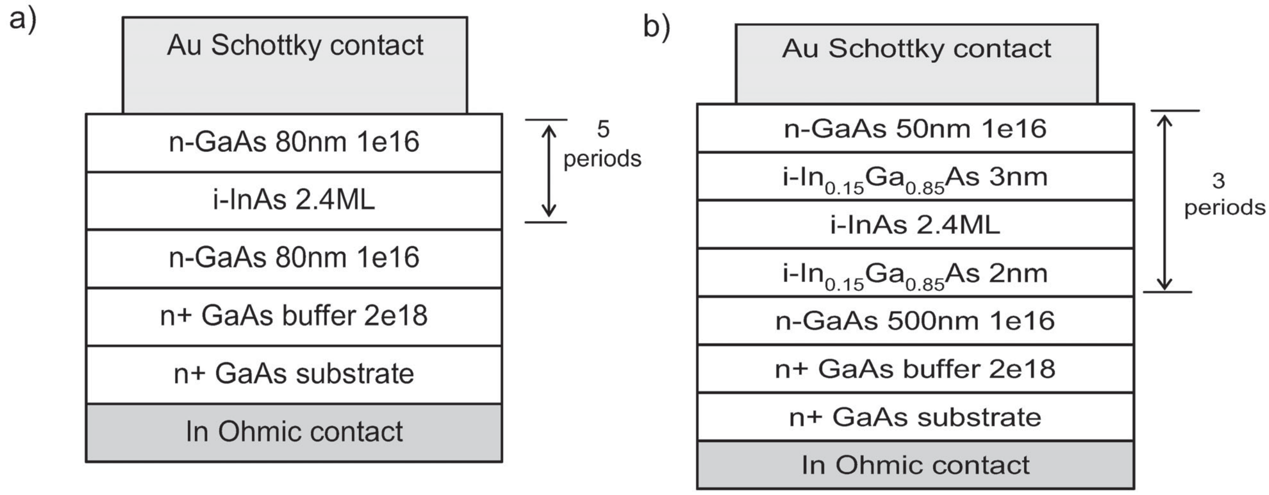

Fig.1. Scheme of the investigated structures:
a) with InAs QDs in the GaAs matrix, b) with InAs QDs in the middle of InGaAs QWs

For measurements two types of structures were used: containing multi-layers of QDs and containing combined layers consisting of 3 InAs QWs where each has a layer of QDs settled down inside, shown on Fig.1 a,b.

As one can see the investigated structures were distinctly differed by physical mechanisms of the capturing process. In the first case (this type of samples is described on Fig.1a) layers of QDs were built in directly to a GaAs matrix and the filling process of QDs by electrons occured due to capturing of carriers from the conduction band of the GaAs matrix directly.

In the second case QDs layers were placed in the middle of the QWs (see. Fig. 1b). It is necessary to note that in the structures where a QDs layer placed inside a QW there are created more acceptable conditions for filling of the QDs localized states from two-dimentional minizone states which were very likely created in the QWs.

To increase a phenomenon of the influence of a charge located in QDs, an area of the structure where layers of QDs settled down was poorly alloyed by the impurity, and the quantity of the QDs layers varied from 3 up to 5.

Capacitance measurements were made by means of the capacitance bridge at a frequency of 1MHz at different temperatures and bias voltages applied to the structure.

The results of measurements of the C-V dependences of the investigated structures with atypical behavior were obtained. Namely, in the area of small forward biases a part of the dependence with NDC (See Fig.2 a,b) was observed.

On the basis of data received from independent researches the planar density of an arrangement of QDs in two types of the investigated samples was accordingly $1X10^{11}$ cm^{-2} and $2X10^{10}$ cm^{-2}.

Remarkably, that the concentration of main n-dopant was only $1X10^{16}$ cm^{-3}. So, it is possible to draw a conclusion that the negative charge accumulated in QDs can not only reach the value of the total positive charge caused by ions of donors, but also is capable to exceed it locally many times under certain applied voltage.

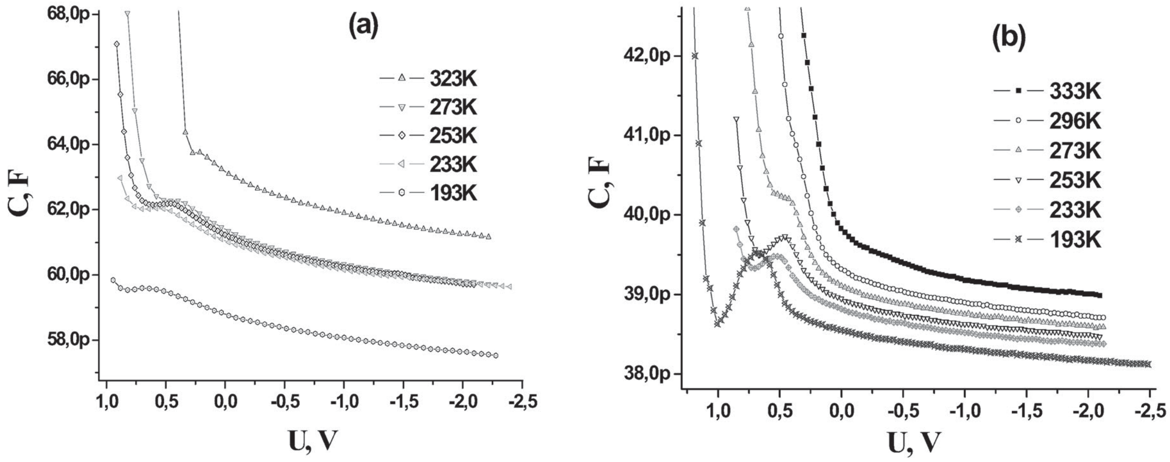

Fig.2 Capacitance-voltage dependences for the diode structures
a) with InAs QDs in the GaAs matrix, b) with InAs QDs in the middle of InGaAs QWs.

To determine the activation energy for emission of charges from electron states we use Deep Level Transient Spectroscopy (DLTS). The basis of the method is a measurement of the time constant of a transient caused as charges are emitted from the states. To create non-equilibrium conditions filling pulses of different amplitude applied to the structure in the straightforward direction and bias voltage pulses applied to the structure in the back direction were used. C-V measurements were used to found input parameters (amplitude of the filling pulse and bias voltages) for DLTS investigation. One can see from C-V curves that the forward bias about 0.5÷1V is the bias where some deviations from traditional behavior are occurred.

Impact of quantum dots in the investigated structures was observed from DLTS measurements under filling pulse more than 0.5V(Fig.3.a,b).

The activation of the charge emission process by temperature causes the time constants to decrease exponentially as temperature is increased. Arrhenius plots can be used to determine the activation energy and the capture cross-section of each state.

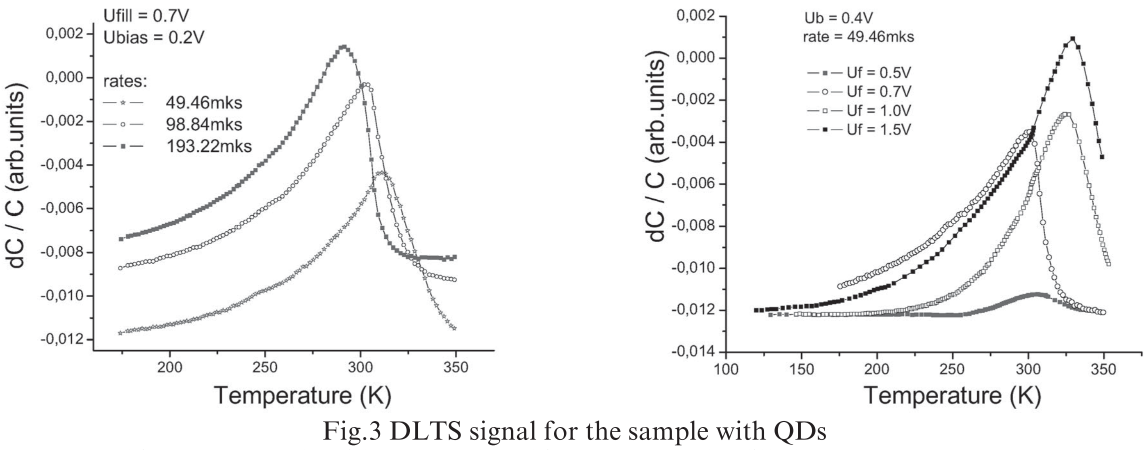

Fig.3 DLTS signal for the sample with QDs
a) Ubias = 0.2V and Ufill = 0.7V ; b) Ubias = 0.4V and Ufill changes from 0.5 to 1.5V.

The dynamics of the base QDs level was investigated. With increasing bias voltage and with constant value of the filling pulse the base energy level was shift to higher values. One can see DLTS spectra for bias voltage 0.4V and different filling pulses: 0.7, 1.0 and 1.5V. Activation energy of the base level of QDs decreases with increasing filling pulse from 350meV to 282meV. And it is necessary to note that when the filling pulse was 0.5V and below DLTS signal from the QDs base level was vanished (Fig.3.b).

III. Theory and discussions of experimental results

Here we obtained numerical simulation of the C-V dependences of the Shottky diode with embedded QD layer taking into account two energy levels inherent to QDs systems very often.

Let us consider the contact between metal and semiconductor with embedded QDs layers at distance of L_{dot} from contact, the width of which is disregarded to simplify our model. Suppose that spatial distribution of QDs can be modelling by means of delta-function.

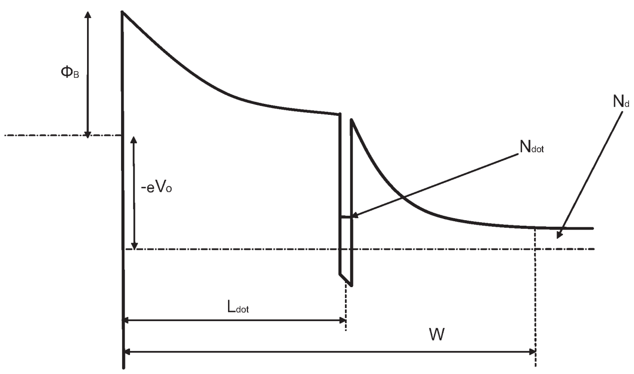

Fig. 4 Zone-diagram of metal-semiconductor contacts with QDs layer in SCR

The following equations set with following boundary conditions were obtained:

$$\frac{d^2\varphi}{dx^2} = -\frac{eN_d}{\varepsilon\varepsilon_0} + \frac{en_{dot}}{\varepsilon\varepsilon_0}\delta(x - L_{dot}) \quad (1)$$

$$\varphi(w) = 0 \quad (2)$$

$$\left.\frac{d\varphi}{dx}\right|_{x=w} = 0\,. \quad (3)$$

The charge density, in the right-hand member of Poisson's equation, consists of two components: N_d — is the constant charge density of ionized impurity and n_{dot} — is the charge density of states accumulated in QDs.

The following solution of equations at this case can be obtained:

$$\varphi(x) = -\frac{eN_d}{2\varepsilon\varepsilon_0}(x-w)^2 + \\ + \begin{Bmatrix} 0, x < L_{dot} \\ \frac{en_{dot}}{\varepsilon\varepsilon_0}(x - L_{dot}), x > L_{dot} \end{Bmatrix} + \frac{en_{dot}}{\varepsilon\varepsilon_0}(L_{dot} - x)\,. \quad (4)$$

At big enough reverse bias the presence of layers of QDs does not make any effect on the distribution of a charge and potential profile of Shottky diode as energy levels of QDs settle down above the quasi Fermi level and QDs states are free from electrons and formula (4) tends to be classical[8,9].

When applied reverse voltage is deacreased, Fermi level E_f approaches to the energy level E_{dot} that leads to the energy states are infilled by electrons, therefore, n_{dot} is increased in compliance with Fermi-Dirac statistic:

$$n_{dot}(V_{dot}) = N_{dot}\frac{\eta}{1+\exp(\frac{E_F - E_{dot} - eV_{dot}}{kT})}\,, \quad (5)$$

here $N_{dot} = N_{surf}\frac{m}{S}$ — is the effective density of QDs, m — total number of layers of QDs in array, S — total linear thickness of QDs array, η — is the quantity of electrons captured to each QDs. As it was estimated in [2] η parameter can be changed between 4 and 8 depending on QDs size.

While increasing of the forward bias, the quasi Fermi level shifts upwards and statistical factors of the filling of the QDs states should increase.

At the certain external voltage the quasi Fermi level reaches a position of the QDs energy level.

Actually, when measuring capacitance-voltage characteristic, we assign constant voltage to the structure V and alternative testing signal V_w at the measuring frequency *f*.

As the result of applying of static voltage, the QDs states accumulate a significant negative charge due to filling by electrons. This charge can not follow alternative testing signal V_w because filling time for the first QDs energy level $\tau_f >> 2\pi / f$.

So, electrostatic equation for the potential in this case can be written

$$-\Phi_B + qV = -\frac{eN_d}{2\varepsilon\varepsilon_0}w^2 + \frac{en_{dot}}{\varepsilon\varepsilon_0}L_{dot}\,. \quad (6)$$

Thus, voltage V as a parameter that defines SCR width is done in (6), changing of which depending on voltage, gives us barrier capacitance

$$C_{bulk} = \frac{\varepsilon\varepsilon_0}{w}\,. \quad (7)$$

Thus, to obtain equation that indirectly defines dependence $w = w(V)$, place (5) into (6) and find:

$$w^2 - \frac{2\varepsilon\varepsilon_0}{eN_d}(\Phi_B - V) + \frac{2N_{dot}}{N_d}\frac{\eta}{1+\exp\left(\dfrac{E_F - E_{dot} - \dfrac{e^2 N_{dot}}{2\varepsilon\varepsilon_0}(L_{dot}-w)^2}{kT}\right)}L_{dot} = 0 \quad . \tag{8}$$

Direct dependence obtaining $w = w(V)$ with analytical elementary functions in general case is impossible. So to calculate w on these conditions we used only numerical solution.

At the external voltage V when quasi Fermi level approaches to the energy level E_{dot} in QDs testing signal V_w can cause recharging of the exiting energy states. It is necessary to note, that time of recharging process for these states by electrons from conduction band strongly depends on energy position of QDs states.

So, to calculate capacitance-voltage characteristic of such contact with QDs in zero approaching when all charge in QDs states can be completely recharged at the measuring frequency *f*, the common capacitance of the structure should be written[8,9]

$$C = C_{bulk} + C_{dot} , \tag{9}$$

where, according to the definition of differential capacitance

$$C_{dot} = e\frac{dn_{dot}}{dV} . \tag{10}$$

The results of numerical C-V simulation are presented on Fig. 5 .

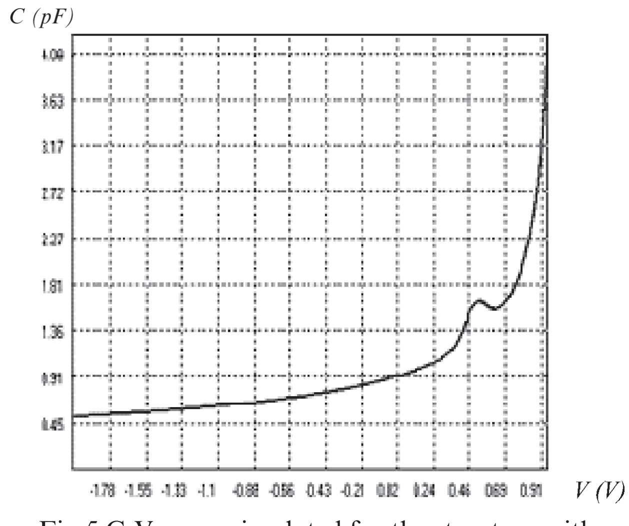

Fig.5 C-V curve simulated for the structure with 5 layers of QDs with $N_{ss} = 10^{11} cm^{-2}$, $\eta = 4$ taken at T=300 K.

It could be assumed, that depending on the position of QDs in the structure the range of voltages (when the area of the C-V dependence with NDC could be observed), can move from the range of forward to small reverse biases.

It is ramarkable that the accumulation of the negative charge in the QDs layers can cause essential redistribution of the electric field and potential profile in SCR. It leads to the creation in the structure of two areas, before and after these QDs layers, with comparatively different distributions of the charge and, possible, opposite directed electric fields around them.

It is necessary to underline that C-V curves reveal distinctly different temperature dependences for the samples with the layers of QDs only and samples with the QDs layers inside QWs. For both of these cases the C-V parts with NDC can be clear experimentally observed.

It is evident from experimental results that the part of the NDC appears on the C-V curve at a little lower room temperature for the samples with QDs inside QWs. It is clear, that the process of accumulation of a charge in the QDs through the QWs reveals strong enough temperature dependence in the range of 193-333K. Decreasing of the temperature results in the part of NDC becomes very clear observed and the capacitance reaches the minimum at the lowest temperature. At 193K the amounts of effect consists almost 15 % of the range of changing of capacitance. At the same time, for the samples with QDs without any additional QWs layers, the part of the NDC reveals on the C-V curve already at room and even more high temperatures. However, in this case the part of the NDC scarcely varies in the wide enough temperature range, and the share of the NDC does not exceed 5 % of the range of changing of capacitance.

IV. Conclusions

In the present paper the phenomenon of the negative differential capacitance(NDC) on the capacitance-voltage characteristics of Shottky diode with the layers of QDs and QDs in QWs can be clear experimentally observed.

Numerical simulation of C-V dependences on such parameters, as temperature and concentration of QDs has been carried out. The results of calculations good describe NDC effect and agree well with experimental results.

It is shown, that the part of the NDC in C-V curve reveals distinctly different temperature dependences for the samples with the layers of QDs only and samples with the QDs layers inside QWs.

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