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STUDY OF THERMIONIC AND TUNNEL COMPONENT CONTRIBUTION IN CONDUCTANCE OF InGaAs/GaAs HETEROSTRUCTURES WITH A SINGLE QUANTUM WELL BY ADMITTANCE METHODS

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Abstract. A study of $In_xGa_{1-x}As/GaAs$ heterostructures with single quantum well (SQW) carried out by admittance methods demonstrates two competing emission mechanisms for carriers: thermionic and tunnel. The dependence of thermionic conductance peaks on the reverse bias has resonance character. We noticed a temperature independent plateau on the conductance-temperature spectra, which is always related to the tunnel nature. We guess the observed effect is the resonant tunneling through the two-barrier potential formed at the QW borders due to doping.

Keywords: admittance, heterostructure, single quantum well, thermionic, tunnel

1. Introduction

Semiconductor heterostructures containing quantum wells (QW) have taken strong positions as materials for creating effective electronic devices: lasers, LEDs, photo-sensor elements, high-speed transistors. Such systems differ in the cardinal reorganization of properties due to size effects. Quantum-dimensional structures, in which free charge carriers are localized in one, two or three directions in the area compared with de Broglie wavelength, are characterized by discrete energy spectrum and in specific conditions may reveal a pure quantum-mechanical tunnel effect. The study of tunneling fundamental principles is perspective for further development of nanoelectronics that creates principally new devices, such as resonant tunnel diodes, quantum-cascade lasers, HEMT transistors, etc.

The admittance method is the most prime and efficient research technique, both for bulk semiconductors and for heterostructures with QW [1-3,5,7]. It is known that in doped heterostructures due to redistribution of charge carriers the bottom of conduction band or the top of valence band is bent, forming additional barriers, close to triangular. In Ref. [4] the detailed theoretical and experimental study of capture and emission of charge carriers in heterostructures with QW is presented. It is shown that in the heterostructures containing QW there are two competing mechanisms of charge carrier escape: thermionic emission and tunneling, which make different contribution to total conductance at different temperatures. In this work the isotype *n*-type heterojunctions $In_xGa_{1-x}As/GaAs$ (x = 0.065 … 0.29) with elastically strained single quantum well (SQW) grown by MOCVD were investigated [1,2]. The sample structure is presented in Fig. 1. The active layer thickness of the samples was 6.0…9.5 nm. The structure parameters and its quality were controlled by local cathodoluminescence, HRXRD, etc. The measurements were taken in the temperature range 10–375 K, voltage range ±40 V, and the frequency range of a test signal was 20 Hz – 2 MHz.

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It was found that at small indium content in the solid solution, it is impossible to notice in the conductance spectra the features related to the tunnel emission, because of the small band discontinuity giving a response, which cannot be registered even at low temperatures. This fact is illustrated in Fig. 2.

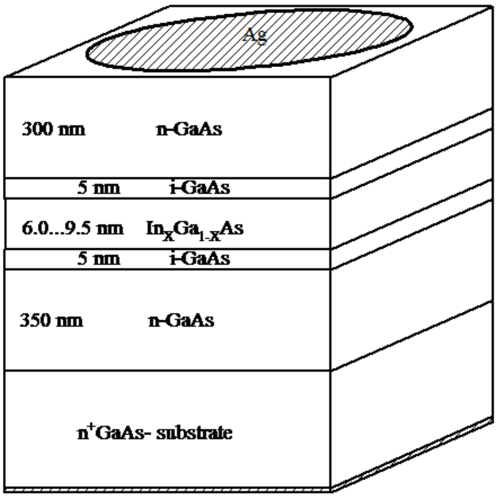

Fig. 1. Structure of samples with SQW InGaAs/GaAs

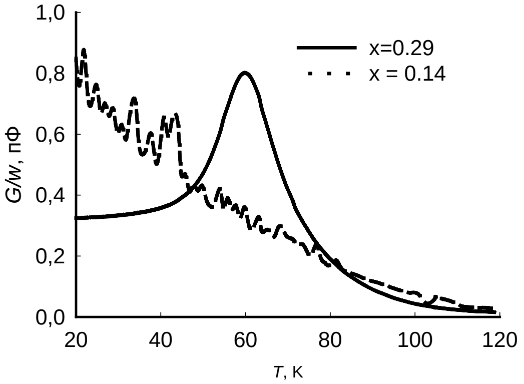

Fig. 2. Temperature spectra of conductance for two different compositions of solid solution
$In_xGa_{1-x}As$:
Firm line, $x = 0.29$
Dotted line, $x = 0.14$

Earlier we investigated pseudomorphism in similar samples and its influence on electronic characteristics of structure [2]. The experimentally obtained dependence is close to a straight line with little bowing. From fitting the curve to parabola, we had proposed the expression:

$$\Delta E_c = 0.814x - 0.21x^2 . \qquad (1)$$

In this study, we analyze the contribution of tunnel conductance to the total response of the system.

2. Experimental results and discussion

The best qualitative characteristics were obtained for structure $x = 0.29$ (the end of pseudomorphism growth). The results are presented in Fig. 3. Here the characteristics CV-GV are located in the center, the temperature spectra of conductance in the reference points of the CV-curve are outside; the points just referred to belong to the plateau, to the plateau adjacent regions, and far from it. From the figure it follows that the delay effects begin to play an important role at low temperatures. At temperatures close to RT, the SQW manages to relax on the test signal frequency (the quasi-static measurement mode is implemented). The conductance-voltage (GV) characteristics of the structure demonstrate clearly the complex resonance mechanism of active conductance formation for the structure with SQW. The strong modification is experienced by the conductance temperature spectra depending on the reverse bias. Indeed, we have shown in [7] that the conductance spectra for QW structure is influenced by the applied bias unlike a deep center evenly distributed in the structure.

The peaks are the most clearly expressed at the reverse bias -2.3 V that corresponds to the part of CV characteristic adjoining the plateau from the small biases. This area is responsible for the beginning of intensive thermionic emission of charge carriers from quantization levels with the electric field penetrating into the QW. The temperature shift of the conductance maximum on frequency confirms the thermally activated nature of the process studied. The observed phenomenon has a resonance character and exists in the narrow voltage range about 0.5 V. Depending on the test signal frequency ω, the maximum burst of charge carriers occurs at temperatures corresponding to the condition of optimum carrier escape from the energy level:

$$w = e_n . \tag{2}$$

At the same time, the thermal emission rate from a level is defined by the expression:

$$e_n = AT^p \exp(-E_a / kT) , \tag{3}$$

where A is a temperature independent coefficient, E_a is the activation energy of charge carriers from the level, k is Boltzmann constant. The value of p is defined by the nature of the emitting center and is different for a deep center in the bulk semiconductor ($p = 2$) and for a quantization level in the quantum well ($p = 1/2$) [8]. The activation energy of charge carriers from levels was determined by plotting the temperature dependence of emission rate constructed in Arrhenius coordinates (without T^p multiplier) (Fig. 4).

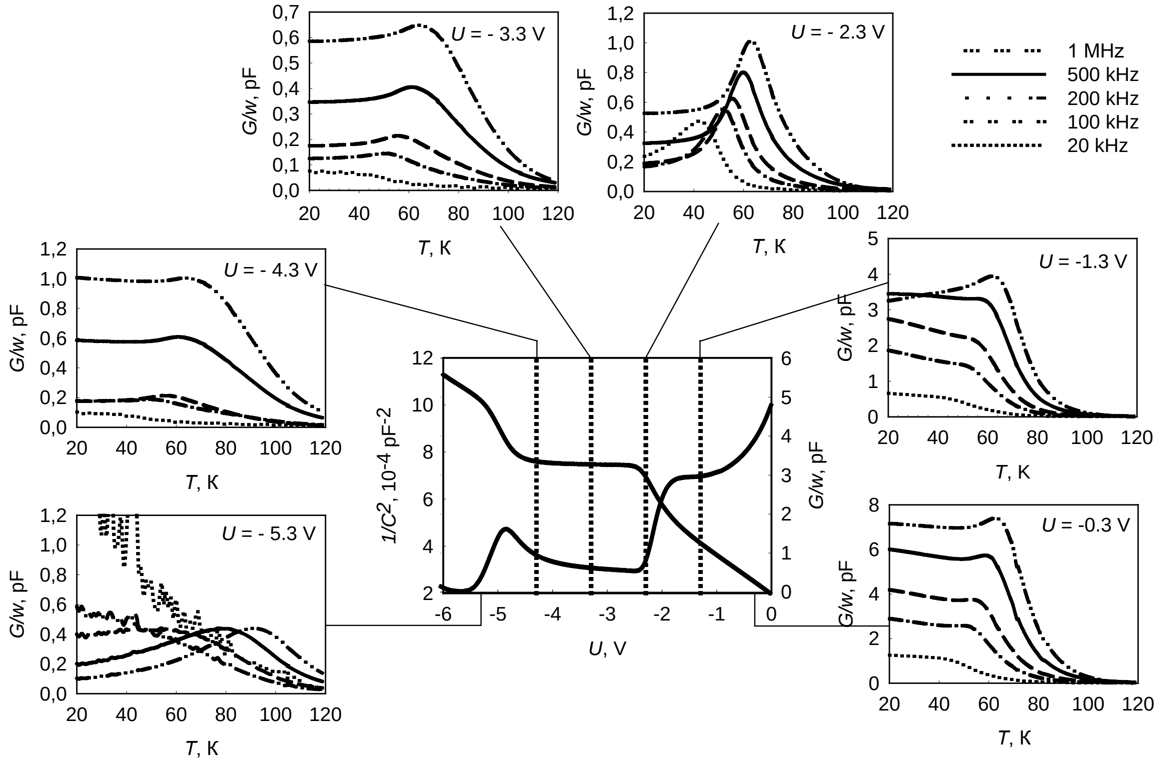

Fig. 3. Generalized results of the admittance measurements for the structure with QW In$_{0.29}$Ga$_{0.71}$As/GaAs

The activation energy, experimentally obtained for emission of charge carriers from QW, is significantly less than the depth of quantization levels in QW and needs separate justification. The point is that the definition of activation energy from a slope of Arrhenius plot is based only on thermoactivated interpretation of charge carriers' emission. The competing tunnel emission with the temperature independent rate increases the total emission rate [6], especially at low temperatures when the contribution of the tunnel component is raised.

It is illustrated in Fig. 5: defined from the experiment the result dependence of $n(e_n) = f(1/T)$ (shown by dotted line) manifests the deviation from a straight line in the low temperature area, and its standard processing by least squares method results in the underestimated E_a value.

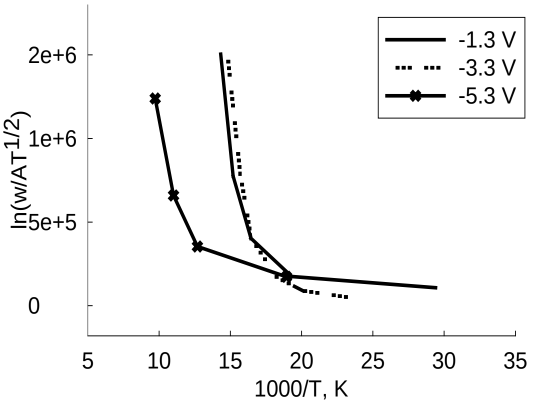

Fig. 4. Temperature dependence of charge-carrier-emission rate from QW in Arrhenius coordinates

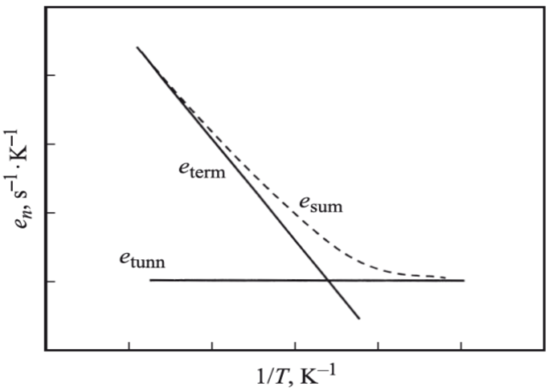

Fig. 5. Calculation of "apparent" activation energy. Curves are calculated using the values: e_{tunn} is the tunnel emission rate, e_{term} is the thermoemission rate, e_{sum} is the total emission rate

Therefore, it is necessary to consider the activation energies, found from conductance spectra by means of drawing Arrhenius curves, only as the "apparent" values; the determination of true values is not possible without special modeling the quantum levels depth in QW. Thus, the net activation energy for charge carrier emission from SQW should be determined by the high-temperature part of Arrhenius curve, minus the tunnel component. Such derived activation energy deviates in the considered case from 36 to 70 meV, depending on the reverse bias.

For the adequate determination of activation energy, we will address to Fig. 3. In the region of thermionic response (at -2.3 V) the activation energy, determined by the Arrhenius curve, reaches the maximum and the experimental points of the Arrhenius curve most exactly keep on a straight line. At other reverse biases, where the thermionic component is expressed poorly against the tunnel background, the experimental points in the Arrhenius plot significantly deviate from the straight line that leads to the considerable decrease of “activation energy”. Thus, the variation of activation energy, derived from the experiment, is caused by the different contribution of tunnel and emission components.

3. Conclusions

The study of high-quality heterostructures with SQW by admittance spectroscopy confirms the existence of two competing mechanisms for emission of charge carriers: thermionic and tunnel ones. It is shown that thermionic peaks in the conductance spectra have resonance character, showing the maxima in the narrow region of reverse biases. The "shelves" in the spectra corresponding to tunnel component at reverse biases 0–3.0 V accepted the maximal value at -0.3 V, and then had sharp fall in more than 10 times. Such behavior of tunnel component can be explained on the basis of resonance tunneling. For the case considered, it is necessary to bear in mind that the top part of the band diagram for doped heterostructures with a SQW represents a two-barrier structure in energy region $E > 0$. It was shown earlier that the structure with identical barriers (the equal width and height) has the greatest probability for carrier tunnel transmission. In this case, the probability for resonance tunneling is maximal. A minor relative change of parameters for one of barriers leads to a strong reducing of transfer coefficient. This qualitative conclusion, based on analytical calculation, allows explaining the experimental results obtained here. Really, at small reverse biases, the external electric field does not reach yet the QW region, and the QW remains with symmetric barriers, identical in form. At the same time, the "shelves" on temperature conductance spectra get the maximal values. On increasing reverse bias the left-hand edge of space charge region begins "to rise", the symmetry of barriers is broken and the tunnel transfer probability drastically falls. In the experimental results, it is expressed by sharp falling of the "shelf" at $U = -1.3\,\text{V}$. Address now to Fig. 6 where the temperature spectra of conductance depending on the reverse bias are presented.

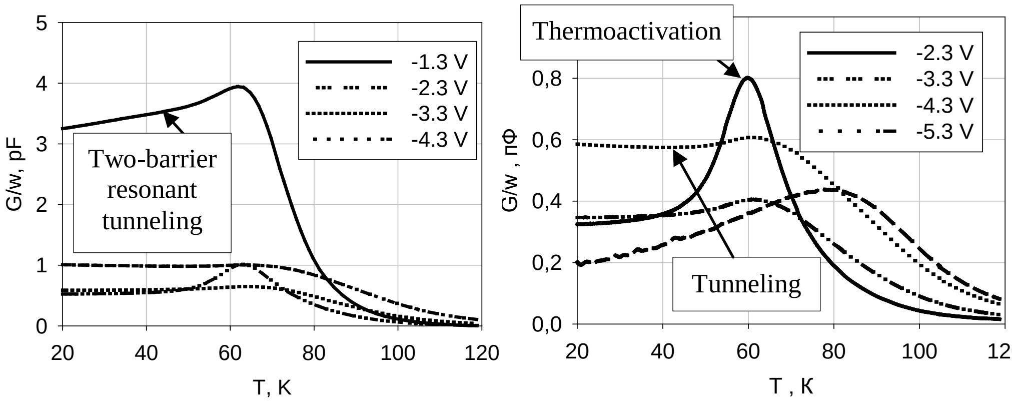

Fig. 6. Conductance temperature spectra. Main mechanisms of carrier charge emission: two-barrier resonant tunneling, thermoactivation, tunneling through a single triangular barrier

Changing the predominating role in the carrier emission goes in the following order. At low reverse biases, it is the resonance tunneling across the two-barrier structure formed at the QW top due to doping. As soon as the edge of SCR approaches the QW, the thermo activation begins to play the dominant role. And finally there is the second turning to tunneling - through a triangular barrier. It is worth noting that the maximal response is provided by the resonance tunneling al low reverse biases. Its value exceeds the thermo activated contribution one order. To our opinion, this effect is very perspective for the device applications.

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