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Ionized states in the III–V heterostructure measured by low-temperature capacitance spectroscopy with optical excitation

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Abstract. The photo-capacitance spectroscopy at low temperature is shown to be a sensitive technique for characterization of the semiconductor structures. This technique was applied to the study of III–V heterostructure with InP quantum dots. Several types of the deep states which can be photo-ionized were found in the structure. Some of this states shows sensitivity to photon energies far below the bandgap of all materials involved.

Introduction

Capacitance spectroscopy and its various modification such as deep level transitional spectroscopy (DLTS) provides a powerful tool for the characterization of the semiconductor structures [1]. However the basic theory of such a measurements is rooted on the classical notions of the thermal ionization of donors or acceptors. This approach gives the elegant tools, such as depletion layer approximation, but at the same time imposes the serious restrictions which results, for example, in the poor resolution of DLTS.

This restrictions can be easily overcame by mere changing the measurement conditions further away from the thermal equilibrium. Probably the most clear and widely adopted example of this "nonequilibrium philosophy" is the technique of photo-conductive measurements of bulk semiconductors. By using the nonequilibrium photons, it allows investigation of the states over the entire bandgap at a single temperature chosen from the considerations of the detection convenience.

The increasing complexity of interesting subjects for modern semiconductor science and applications demands further sophistication of the investigation techniques in the same direction, that is, away from the equilibrium. One possible way is the using of ultrashort optical pulses, which can reveal processes as fast as interband relaxation [2]. Another quite successful approach, low-temperature capacitance spectroscopy [3], has an advantage of detecting tunnel current which is more selective than thermocurrent and also does not require the electrical conductance of the whole sample. Recently this technique was used [4] for study of the charged states of InAs self-assembled quantum dots (QDs).

In this work we are presenting an attempt to apply the similar technique to the heterostructures with InP QDs which studies are more difficult because of generally worse quality of ternary composition barriers and interference from the bulk GaAs substrate which interband transitions overlap with the optical transitions in the QDs.

1 Experimental

The sample used for this experiment is grown by the gas source molecular beam epitaxy on the GaAs n-doped substrate and contains GaAs buffer with short GaAs/AlAs superlattice inside, $In_{0.5}Ga_{0.5}P$ barrier separated from the buffer by thin AlAs layer, and the single layer of InP QDs covered by the second half of the barrier layer. Detailed microphotograph of the sample is presented elsewhere [5]. The gold electrode with transparency of about 5% and area of 10 mm^2 is deposited on the top of sample, and back side of the substrate is coated by the indium.

This sample is mounted in the optical cryostat filled by a superfluid helium and both sample surfaces are wired to the outside by separate shielded conductors. Both shields are grounded and connected to the cryostat body. The substrate contact is used for applying the sweepable DC bias to the sample with small 100 kHz AC modulation added via the differential amplifier. The top semitransparent contact is connected to the input terminal of the current amplifier at the virtual ground potential. When reverse bias is applied, a considerable leakage current occurs through the point defects shunting the epitaxial layers. Loop for this current is completed through the low output impedance of differential amplifier and low input impedance of current amplifier.

The signal from the current amplifier is fed to the lock-in detector which is referenced by the same 100 kHz modulation. Quadrature component of the current is proportional to the capacity of the sample. This component is fed to the second lock-in detector which reference is locked to the light chopper modulating the sample illumination. Thus, the second lock-in records the sample capacitance change by the action of light. The CW Ti:sapphire laser and the combination of incandescent lamp and monochromator are used as tunable light sources.

2 Results and discussion

Capacitance–voltage profile of this sample, measured at 2 K, is essentially flat and even non-monotonous in the domain of reverse bias. This is the direct consequence of inapplicability of the depletion layer approximation at low temperatures.

The photo-capacitance–voltage (ΔC versus V) profiles excited by the laser light of different wavelengths are presented in Fig. 1. The traces were recorded by linearly sweeping the bias voltage back and forth, and some traces indicate a hysteresis-like splitting which represents the very slow (comparing with the sweep rate of about 1 V/s) charging and discharging processes in the sample. Note that the photo-capacitance is always positive, that is the additional light can only release additional charge.

The traces show a number of peaks at different voltages. In view of the logarithmic scale in the figure, these peaks are rather sharp providing good resolution of this technique. The width of sharpest feature is comparable to the modulation amplitude. Whereas the position of the peaks requires for interpretation some additional electrostatic considerations, the area below each peak

$$\Delta Q = \int \Delta C \, dV \tag{1}$$

represents the amount of mobile charge released by the illumination because the electrostatic equation $Q = CV$ due to its integral nature is insensitive to the details of charge distribution.

The physical origin of this peaks owes to the presence of internal potential profile in the semiconductor structures which is affected by the external bias. The capacitance measuring technique is sensitive only to the mobile charge, which is constituted from carriers located in

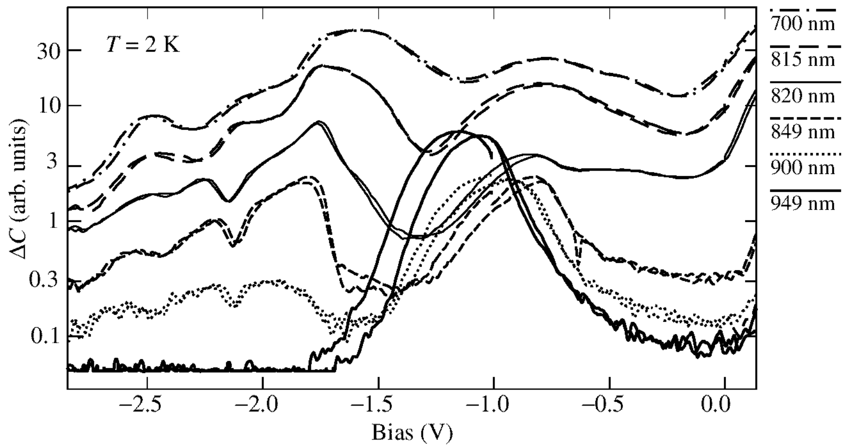

Fig. 1. Photo-capacitance as function of applied bias for different laser wavelengths. Laser power is about 0.6 μW/cm^2 and chopping frequency is 15 Hz for all traces.

the flat regions of the profile. Different portions of the profile are flattened under the different bias, providing a means for the selecting different layers of the sample. Monochromatic light gives an additional selectivity.

The most interesting result is that considerable photo-capacitance signal is observed even when the excitation light falls below the GaAs bandgap, where the sample should be totally transparent. This is a clear indication of the presence of deep states which were also observed in our studies on anti-Stokes photoluminescence [6]. Moreover, the amplitude of the most prominent peak around -1.0 V bias is increasing with longer wavelengths, which means that photo-generated mobile carriers can accumulate during the time comparable to the light chopping period. An additional experiment with the lamp and monochromator as light source has shown that amplitude of this peak continue to grow with decreasing the chopping frequency down to few mHz and that the photo-capacitance signal can be excited with photons as low as 1.0 eV.

3 Conclusion

This work presents the low temperature photo-capacitance spectroscopy as a powerful tool for investigation of the complex semiconductor heterostructures. This technique is used to study the epitaxial structure with InP QDs. A number of types of defects which can be photo-ionized is found in the sample. Some of this defects are sensitive to the infrared light far below the band to band absorption of any material in the structure. Exact identification of this defects needs further investigation.

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