Controllable electron transport in the lateral nanostructure

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ABSTRACT

We report the results of the theoretical investigation of the band structure of a periodically corrugated quantum well and experimental modeling of the well by the periodic microwave waveguide. It is shown that the lateral periodic corrugation allows to control the in-plane electron transport in such quantum well. The electron transport varies from zero to a maximum value upon a shift of one periodic boundary with respect to another on the half period of the corrugation. This transformation corresponds to metal-insulator transition in the nanostructure that can not be observed in a multiple quantum well (MQW) structures using the vertical transport. The metal-insulator transition is caused by the opening of the gap in the energy band diagram of the nanostructure. The observation of the wave transmission through the periodic waveguide has confirmed the theoretical prediction.

Keywords: lateral nanostructure, periodic quantum well, periodic waveguide, tunability, Bragg reflection.

1 INTRODUCTION

The study of two-dimensional electronic systems evokes considerable interest due to the broad utilization of the systems in microelectronics [1-3] as well as for the close relation of this problem to explanation of high temperature superconductivity. Design of new devices are commonly based on exploiting the different configurations of multiple-quantum-well structures and superlattices. Technological advances in this field allow enable the tailoring of electronic properties of the nanostructures by varying of parameters of quantum wells and barriers [4-6]. In these nanostructures, the vertical transport of electrons across quantum wells is commonly used. Despite great progress in this field, a MQW has one main inherent defect: a period of the structure is always greater than a thickness of a single quantum well. Therefore, the electron energy, associated with the period, is always less than the energy of the ground state in the single quantum well. Taking into consideration that the energy level crossing causes important resonance properties of the system, it becomes clear that these resonant properties are excluded from MQW structures using the vertical transport. This defect can be avoided if the in-plane transport of electrons in a quantum well with periodic boundaries is used. In this case there are neither physical nor principal technological restrictions on the relationship between thickness and a period. Moreover, modern technology can create the bias voltage tunable lateral modulation using the same principle as in the MOS transistor [3].

2 THEORETICAL RESULTS

Consider an infinitely deep potential well of thickness d, where both walls have one-dimensional periodic corrugations described by the functions $y_{-d}(x) = -d/2 + \xi\cos(qx)$ for the left boundary and $y_d(x) = d/2 + \xi\cos(qx+\theta)$ for the right boundary, where $q = 2\pi/a$; ξ, and a are amplitudes and a period of the corrugations, the parameter θ is the phase shift between the right and left periodic corrugations. As we mentioned before, a may have a value of the crystal lattice constant or any other value depending on a periodic profile of the boundary. Thus, an electron is in a well bounded by a two-dimensional potential $U(x,y)$

$$U(x,y)=\begin{cases}0 & -d/2 < y < d/2 \\ \infty & y_d(x) \le y \le y_{-d}(x)\end{cases} \quad (1)$$

This potential pattern is illustrated in Fig.1.

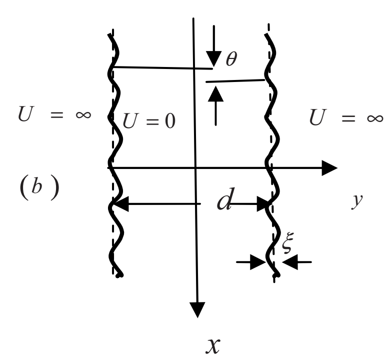

Figure1: Two-dimensional potential energy profile of a periodically corrugated quantum well is shown in the the xy-plane. θ is the phase shift between the left and right periodic boundaries.

The wave function $\psi(x,y,z)$ and the energy E of the electron are found by solving the three dimensional stationary Schrodinger equation [7] with potential (1). The solution of the equation at the boundaries of the Brillouin zone ($k_x^{\pm} = \pm\ q/2$) can be written in the form

$$E_p^{\pm} = E_p \left\{ 1 \pm \frac{\sqrt{2}\,\xi}{d} [1-\cos\theta]^{1/2} \right\}, \quad (2)$$

$$E_p = \frac{\hbar^2 p^2 \pi^2}{2md^2} \quad .$$

$$\delta E_p = E_p^+ - E_p^- = 2\sqrt{2}\, E_p \frac{\xi}{d} [1-\cos\theta]^{1/2} \ , \quad (3)$$

$$m^* = -\frac{1}{\sqrt{2}} \frac{\xi}{d} [1-\cos\theta]^{1/2} \frac{k_p^2}{q^2}\ m \ ,$$

$$k_p = \frac{p\pi}{d}, \qquad p = 1,2,3... \quad (4)$$

The solution (2)-(4) shows that due to the Bragg reflection the energy level splits into two values E_p^+ and E_p^-, separated by the forbidden gap δE_p. It is seen that the band structure and the effective mass of the electron in the quantum well substantially depend on the phase shift θ between two periodic boundaries. The angle measure of the phase shift,
θ , can be written as the function of the linear shift Δx : $\theta = (2\pi/a)\Delta x$. Fig.2 illustrates the transformation of the energy band structure upon a shift the boundaries on a half period of corrugation $\Delta x = a/2$.

3 EXPERIMENTAL RESULTS

The wave properties of a periodic structure depend on a ratio between the wavelength and characteristic dimensions of the structure, therefore, the observed microwave properties are useful for modeling of electron phenomena in periodic quantum structures. The principal condition of observation of the properties, caused by periodicity in solids, is $l >> a$, where l is the electron mean free path, and a is a period of the lateral modulation. It is rigid enough condition that can be met usually at the helium temperature. The advantage of microwaves in such modeling is the very large "mean free path" of the electromagnetic wave, almost matching the electron mean free path in superconductors. So the mentioned condition is always met. Another advantage is that the waveguide, unlike solid, allows to investigate the dispersion of a separate mode. From this point of view, the waveguide can be considered as the empty of electrons crystal. Consequently the microwave experiment allows to model the electron quantum phenomena in micro- and nanostructures and to observe the effect of periodicity in the structures at the most favorable conditions. Here we give the results of the experimental observation of this phenomenon at the microwave range of wavelengths.

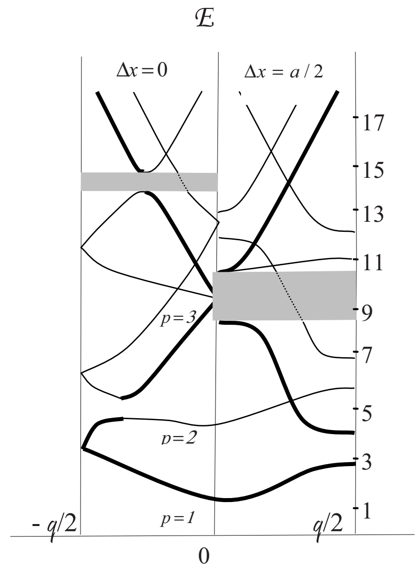

Figure 2: Dispersion $E(k)$ for the periodic quantum well. Here, $\mathcal{E} = E/E_1$, E_1 is the ground electron energy ($p=1$) in the quantum well, $q=2\pi/a$, a is a period of the corrugation. The right side of the graph represents dispersions for the case when the shift Δx between periodic boundaries is equal to the half period of the corrugation ($\Delta x = a/2$), the left – for the symmetric waveguide ($\Delta x = 0$). The shift causes the opening of the gap (shaded area) near the bottom of the $p=3$ 2D-subband.

The transmission properties of a planar waveguide, made of two metal plates having the identical sinusoidal profile with ξ and a equal correspondingly to 0.415 cm and 3.15 cm in experimentation. The length of the structure was 82 cm which corresponded to 26 periods of the corrugation. The upper plate could slide with respect to the lower forming the phase shift Δx between them.

The standard microwave setup (Fig.1), consisting of the oscillator, two couplers, the Agilent E44196 power meter and two pyramidal horn antennas, was used for the measurements. The propagation of the *TE* wave, having the polarization vector ***E*** parallel to the grooves of the corrugation (the *z*-axis), was investigated at the microwave range of frequency 8-12 GHz.

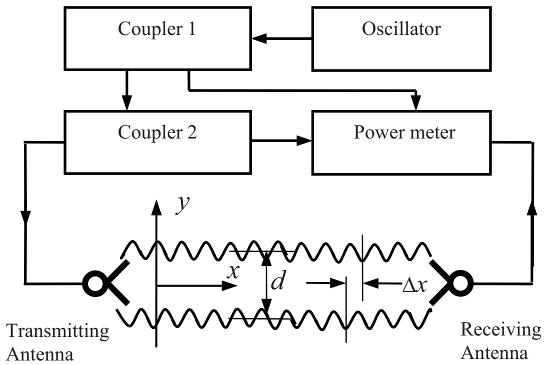

Figure 3: Experimental setup for measuring the transmission properties of the periodically corrugated waveguide that models the periodic quantum well. The *z*-axis is perpendicular to the plane of the picture. Tuning is achieved by a shift Δx of the upper plate along the *x*-axis.

Fig.4 illustrates the experimental observation of microwave transmission ("metal-insulator transition") through periodic waveguide at 10.42 GHz.

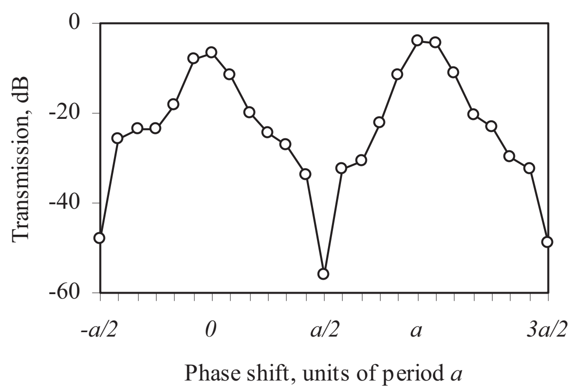

Figure 4: The measured transmission through the corrugated waveguide at a fixed frequency of 10.42 GHz is plotted as a function of the phase shift Δx between the plates.

For this measurement, the initial position of the plates was chosen at $\Delta x = a/2$ and then one plate was gradually moved back and forth on one period of the corrugation. The graph shows that the transmission varies from the minimum to maximum value upon a shift of one periodic plate with respect to another on the half period of the corrugation, *a*/2.

These experimental results are in a good agreement with formula (2), which describes the controllable band gap in the spectrum for the periodically corrugated quantum well or waveguide.

4 CONCLUSION

In conclusion, the transmission properties of a periodically corrugated quantum well have been investigated theoretically and experimentally. The experimental verification has been done by the modeling the quantum well by the corrugated waveguide. The 1.24 GHz band gap in vicinity of the cutoff frequency of the 3rd mode has been observed. Upon a shift of one of the plates with respect to another on a half period of corrugation, the gap vanished. In latter case, that of the congruent boundaries, an electromagnetic wave was propagated in the periodic waveguide without Bragg reflection indicating on gapless folding of dispersions in the spectrum for the periodic structure.

This paper has described an experiment on the tuning of the 1.24 GHZ gap at a thickness of 4.5 cm. The maximum width of the gap, however, could be easily varied from 3.5 GHz down to a few KHz on altering the waveguide thickness between 4 cm and 10 cm.

In solid state terminology, this spectrum transformation corresponds to the metal –insulator transition, when the Fermi energy matches the gap.

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