APPLICATION OF QUANTUM-SIZE STRUCTURES IN MICRO- AND NANOELECTRONICS DEVICES

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Abstract: The last three decades of development in solid-state physics have been characterized by the fact that the main objects of research are increasingly not massive crystals, but thin films, multilayer thin-film systems, conducting filaments, and small-sized crystallites. The fact that quantum-size structures are currently at the center of attention is due to the intensive development in recent years of semiconductor structure manufacturing technology – molecular beam epitaxy (which represents an improved version of the thermal evaporation technique under ultra-high vacuum conditions), nanolithography, and the discovery of the phenomenon of self-organization of nanostructures (methods of production using the effects of spontaneous formation of nanostructures).

Keywords: Semiconductor, nanostructure, heterostructure, lasers, energy spectrum, two-dimensional system, threshold current, injection laser, generation, light quanta.

The entire complex of phenomena usually understood by the words "electronic properties of low-dimensional electronic systems," and the numerous new types of electronic devices that use these properties – all of this is based on one fundamental physical fact: the change in the energy spectrum of electrons and holes in structures with very small dimensions. In such systems, most electronic properties change significantly – a large number of new, so-called size effects arise. Quantum-size structures, in which free charge carriers are localized in one, two, or all three coordinate directions in a region with dimensions on the order of the de Broglie wavelength of the carriers, are distinguished by the most radical restructuring of properties. At this point, the laws of quantum mechanics come into force, and the most fundamental characteristic of the electronic system – its energy spectrum – undergoes a change. The spectrum becomes discrete along the coordinate in which motion is restricted. If motion is restricted along one or two directions, then under the influence of external fields and interactions with scattering centers (phonons, impurities), not three but only two or one component of the electron and hole momentum may change, as a result of which the carriers behave as a two-dimensional or one-dimensional gas. Quantum structures in which carrier motion is restricted in all three directions resemble artificial atoms. Here the energy spectrum is purely discrete. Quantum-size structures possess a whole set of unique properties, very far from those that can be observed in a system of ordinary, three-dimensional electrons and holes. Such structures can serve as the basis for creating new types of semiconductor devices, primarily for opto- and nanoelectronics.

The most common type of semiconductor laser is the double heterostructure laser, where the active region is a thin layer of a narrow-gap semiconductor between two wide-gap semiconductors. Such double heterostructures based on AIIIBV semiconductor compounds were proposed and realized by Zh.I. Alferov and others. At a sufficiently small thickness of the active region, the heterostructure begins to behave as a quantum well, and the quantization of the energy spectrum in it significantly changes the properties of lasers.

The main influence on the properties of lasers is exerted by the change in the density of states that occurs under the influence of size quantization. While in a bulk semiconductor in the immediate vicinity of the band edge this value is small, in a quantum-size system it does not decrease near the edge, remaining equal to $m/\pi\hbar^2$. Due to this fact, the conditions for creating population inversion in two-dimensional systems turn out to be more favorable than in three-dimensional systems. The creation of lasers with a quantum-size active region made it possible to obtain continuous generation at room temperature and subsequently reduce the threshold current of the injection laser to record low values, currently amounting to about 50 A/cm^2.

Fig. 1. - Double-sided laser heterostructure: a) in a state of thermodynamic equilibrium; b) during operation.

[Note: Figure 1 referenced in the original text is not included in the PDF content provided]

Due to the different energy dependence of the density of states, not only the magnitude of the threshold current changes, but also its temperature dependence. It becomes weaker, as a result of which continuous generation can be obtained not only at room temperature but also at higher temperatures.

Another feature of quantum well lasers is the possibility of their frequency tuning. The minimum energy of emitted light quanta is: $\hbar\omega = Eg + E_1^e + E_1^h$

It changes when the dimensions of the quantum well change, i.e., by changing the width of the quantum well, it is possible to tune the generation frequency, shifting it toward the short-wavelength side compared to lasers with a wide (classical) active region.

In quantum dots, the energy spectrum changes more radically than in quantum wells. The density of states has a delta-function-like form, and as a result, there are no states that do not participate in the amplification of optical radiation but contain electrons. This reduces energy losses and, as a consequence, reduces the threshold current.

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