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DSE3T (Nano Materials and Applications)

Topic – Applications (Part – 1)

Infrared Detectors:

Infrared transitions involving energy levels of quantum wells have been used for infrared photo detectors. Sketches of four types of these detectors are presented in Fig. 1. The conduction band is shown at or near the top of these figures, occupied and unoccupied bound-state energy levels are shown in the wells, and the infrared transitions are indicated by vertical arrows. Incoming infrared radiation raises electrons to the conduction band, and the resulting electric current flow is a measure of the incident radiation intensity. Fig. 1(a) illustrates a transition from bound state to bound state that takes place within the quantum well, and Fig. 1(b) shows a transition from bound state to continuum. In Fig. 1(c) the continuum begins at the top of the well, so the transition is from bound state to quasi-bound state. Finally in Fig. 1(d) the continuum band lies below the top of the well, so the transition is from bound state to miniband.

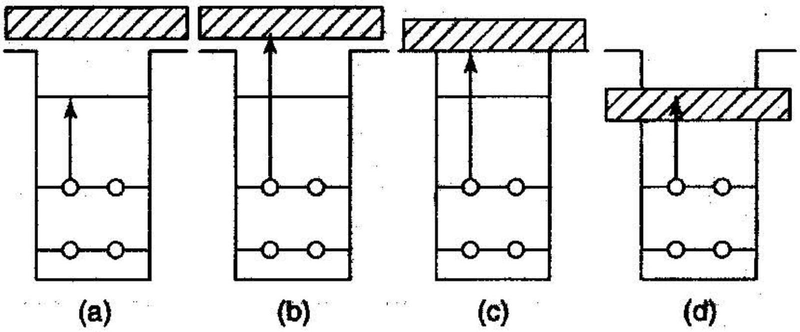

Fig. 1

The responsivity of the detector is the electric current (in A) generated per watt (W) of incoming radiation. Fig. 2 shows the dependence of a GaAs/AlGaAs bound state—continuum photodetector's responsivity on the wavelength for normal and 45^0 incidence. The responsivity reaches a peak at the wavelength

$\lambda = 9.4$ µm, and Fig. 2 shows the dependence of this peak responsivity (Rp) on the bias voltage. The operating bias of 2 V was used to obtain the data as Fig. 2 shows, at that bias the responsivity has levelled off at a high value. This detector is sensitive for operation in the infrared wavelength range from 8.5 to 10 µm.

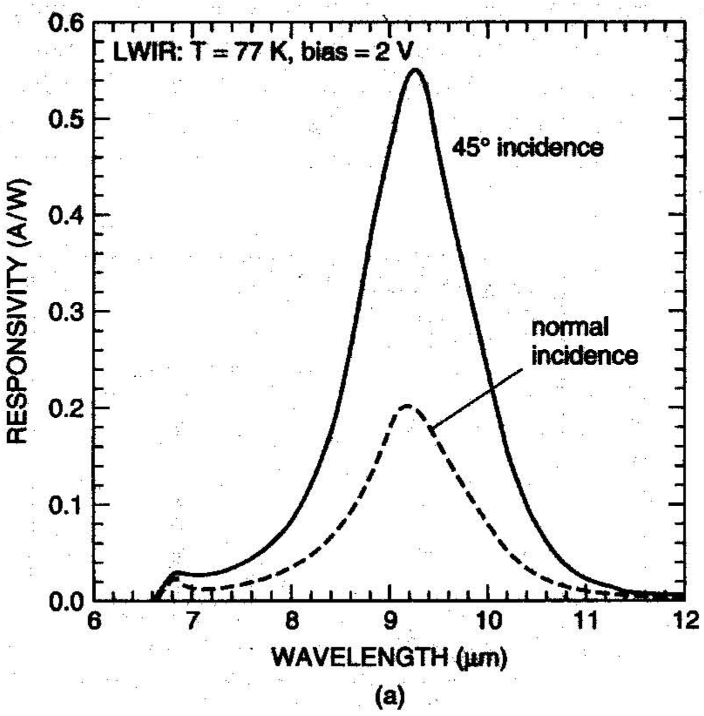

Fig. 2

Single-electron Transistors:

Single-electron devices like the one sketched in Fig. 3 are two-terminal devices, i.e., they are diode-type devices. It is possible to introduce an additional gate and create three-terminal device, a single-electron transistor. In Fig. 3(a), the design of the metallic electrodes on the top of a heterostructure with a two-dimensional electron gas is shown. The gates G_1, G_2, and G_4 form a quantum dot as above; the gate G_3 additionally controls the size and shape of the dot, changing its properties. The single-electron transistor works as follows.

The electron transfer is determined by two factors: the Coulomb charging of the dot and the quantized energy levels in the dot. If the drain is biased with respect to the source, an electric current occurs in the regime of single-electron transfer. By applying the voltage to the gate and changing the quantum-dot parameters, one can change the conditions of electron tunnelling and affect the source–drain current. Examples of modulation of the conductance in single-electron transistors by the gate voltage are presented in Fig. 4.

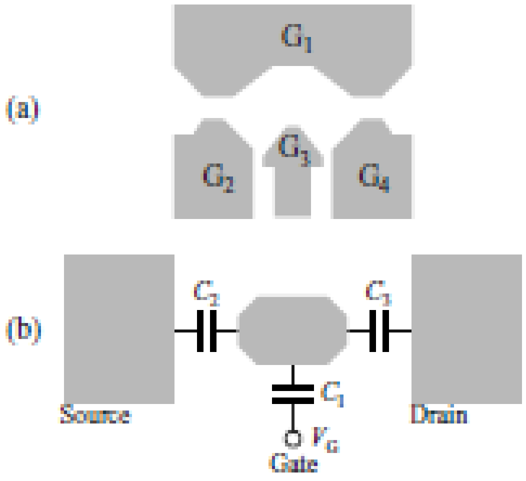

Fig. 3

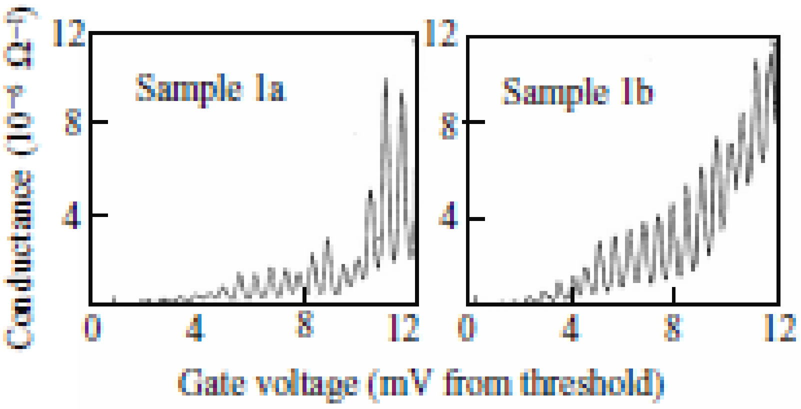

Fig. 4

The devices have almost the same geometry. Their dimensions are large enough to have a number of quantized levels. In Fig. 4 each peak in the conductance corresponds to transfer of one electron, when an energy level enters into resonance with the electron states in the contacts. Though the conductance versus gate-voltage dependences are different, i.e., not reproducible, the peak spacing is the same for both devices. It is determined by the change in the gate voltage required to change the charging energy of the quantum dots by one electron. The figures show clearly that the electric current is modulated significantly by the gate voltage. Thus, for transistors with single-electron transport, strong control of very small electric current may be possible. The problem of fabrication of reproducible devices requires further improvements in technology.

Light-emitting diodes (LEDs):

So far we have studied electronic nanoscale devices, i.e., a class of devices that exploits electrical properties of nanostructures and operates with electric input and output signals. Another class is composed of optoelectronic devices, which are based on both electrical and optical properties of materials and work with optical and electric signals.

In this part, we will analyze a very important class of optoelectronic devices: light-emitting diodes. As their titles imply, the devices were invented to produce light with certain properties. In particular, the energy of the electric current flowing through these diodes is transformed into light energy. These optoelectronic devices have a huge number of applications and deserve consideration in detail.

Historically, light-matter interactions provided some of the first evidence for the quantum nature of matter. It is important to note that an electromagnetic field consists of an infinite number of modes (waves), each of which is characterized by a wavevector and a specific polarization. According to quantum physics each mode may be described in terms of a harmonic oscillator of frequency ω. Correspondingly, the energy separation between levels of this quantum-mechanical oscillator is $\hbar\omega$. This oscillator may be in the non-excited state, which manifests the ground-state or zero-point vibrations of the electromagnetic field. The oscillator may be excited to some higher energy level. If the Nth level of the oscillator is excited, there are N quanta (photons) in the mode under consideration. The classical description of an electromagnetic wave is valid at large numbers of photons: $N \gg 1$.

Besides quantization of the energy, the quantum nature of electromagnetic fields is revealed in the equilibrium statistics of photons. Indeed, photons obey the so-called Boson statistics or Bose–Einstein statistics, which gives the average number of photons of some chosen mode under equilibrium. In order to visualize these processes, we consider a simple quantized system with two energy levels E_1 and E_2 as depicted in Fig. 5. The occupancies of the energy levels of this system correspond to particular states of a system of the electrons. The charged electrons interact with the electromagnetic field. This interaction results in transitions between quantum states of the system. These transitions are frequently referred to as *phototransitions*. According to the quantum theory, the system can change its energy as a result of interaction with electromagnetic waves exclusively of the frequency $\omega = \frac{E_2 - E_1}{\hbar}$.

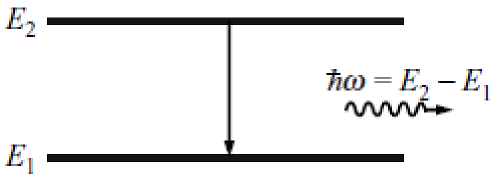

Fig. 5

If the lowest energy level E_1 is occupied, the wave can excite the system into the upper level E_2 and the electromagnetic energy must decrease. One can describe this process as the absorption of one photon because the energy of the electromagnetic field decreases by $E_2 - E_1$. If the system occupies the upper level E_2, it can make a transition to level E_1 as a result of interaction with the electromagnetic field. Then, the electromagnetic energy increases by $E_2 - E_1$. This process represents the emission of a photon with energy $\hbar\omega$. When activated by an external electromagnetic wave, the latter process is called stimulated emission. It is important that, for stimulated emission, each emitted photon has the energy, direction, polarization, and even phase coinciding precisely with those of the stimulating wave.

Quantum Dot Lasers:

The infrared detectors described in the previous part depend on the presence of discrete energy levels in a quantum well between which transitions in the infrared spectral region can be induced. Laser operation also requires the presence of discrete energy levels; that is, levels between which laser emission transitions can be induced. The word laser is an acronym for light amplification by stimulated emission of light, and the light emitted by a laser is both monochromatic (single-wavelength) and coherent (in-phase). Quantum-well and quantum-wire lasers have been constructed that make use of these laser emission transitions. These devices have conduction electrons for which the confinement and localization in discrete energy levels takes place in one or two dimensions, respectively hybrid-type lasers have been constructed using dots in a well, such as InAs quantum dots placed in a strained InGaAs quantum well. Another design employed what have been referred to as InAs quantum dashes, which are very short quantum wires, or from another point of view they are quantum dots elongated in one direction.

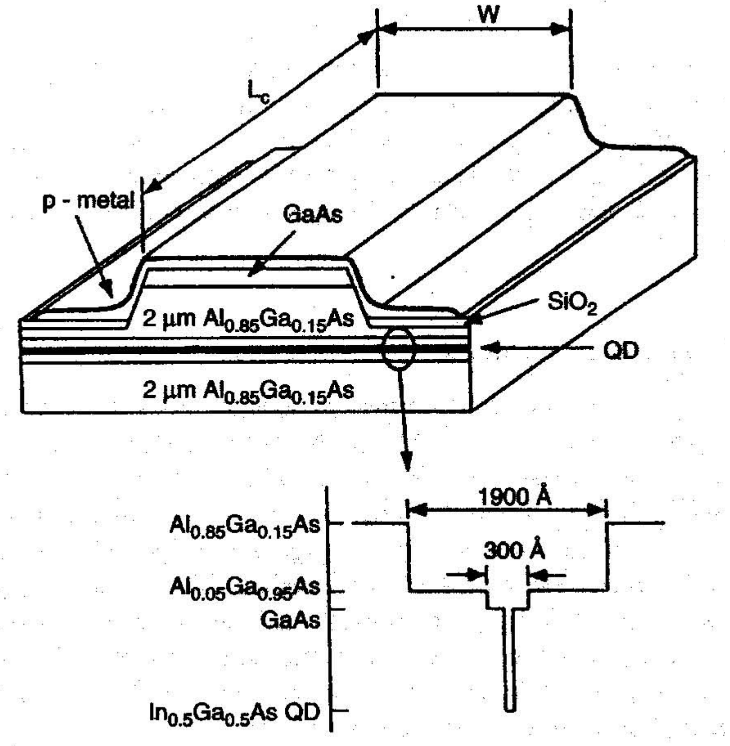

Fig. 6

The present section is devoted to a discussion of quantum-dot lasers, in which the confinement is in all three spatial directions. Conventional laser operation requires the presence of a laser medium containing active atoms with discrete energy levels between which the laser emission transitions take place. It also requires a mechanism for population inversion whereby an upper energy level acquires a population of electrons exceeding that of the lower-lying ground-state level. In a helium-neon gas laser the active atoms are Ne mixed with He, and in a Nd-YAG solid-state laser the active atoms are neodymium ions substituted ($\sim 10^{19}$ cm^{-3}) in a yttrium aluminium garnet crystal. In the quantum-dot laser to be described here the quantum dots play the role of the active atoms. Fig. 6 provides a schematic illustration of a quantum-dot laser diode grown on an n-doped GaAs substrate. The top p-metal layer has a GaAs contact layer immediately below it. Between this contact layer above and the GaAs substrate below the diagram, there are a pair of 21.1m-thick $Al_{0.85}Ga_{0.15}As$ cladding or bounding layers that surround a 190-nm-thick waveguide made of $Al_{0.05}Ga_{0.95}As$. The waveguide plays the role of conducting the emitted light to the exit ports at the edges of the structure. Centred in the waveguide (dark horizontal snipe on the figure labelled QD) is a 30-nm-thick GaAs region, and centred in this region are 12 monolayers of $In_{0.5}Ga_{0.5}As$ quantum dots with a density of 1.5×10^{10} cm^{-2}. The inset at the bottom of the figure was drawn to represent the details of the waveguide region. The length Lc and the width W varied somewhat from sample to sample, with Lc = ranging from 1 to 5 mm, and W varying between 4 and 60 μm. The facets or faces of the laser were coated with $ZnSe/MgF_2$ high-reflectivity ($> 95\%$) coatings that reflected the light back and forth inside to augment the stimulated emission. The laser light exited through the lateral edge of the laser.

This concludes part 1 of this e-report.

The discussion will be continuing in the part 2 of this e-report.

Reference(s):

Introduction to Nanoelectronics, Mitin, Kochelap & Stroscio, Cambridge University Press

Introduction to Nanotechnology, Poole Jr. & Owens, Willey

(All the figures have been collected from the above mentioned references)