HETEROSTRUCTURE DEVICES

All semiconductor devices are made of building blocks, consisting of semiconductor structures with different properties and supplied by some nonsemiconductor parts. This relates to discrete devices and integrated curcuits alike. Junctions of semiconductors doped by different impurities are the most important structures of semiconductor devices. If a junction is formed by regions of the same semiconductor material with one of them doped by acceptor impurities, and the other one by donor impurities, such junction is called the *p–n*-junction, or the *p–n*-homojunction. Semiconductor structures consisting of homojunctions are known as homostructures. More generally, homostructures are defined as semiconductor structures in which doping changes with position. Semiconductor structures with a nonuniform chemical composition are called heterostructures. The simplest heterostructure includes a single heterojunction, which is an interface between two different semiconductor materials. The size of the region where the chemical composition changes can be both small (about a few periods of the crystal lattice) and relatively large (comparable with the size of the device). The first case corresponds to so-called abrupt heterostructure, in contrast to graded (or graded-gap) heterostructure, in which the chemical composition and, in turn, the semiconductor energy band gap change smoothly.

The abrupt heterostructures can be formed by almost all combinations of semiconductor materials, though not all combinations yield heterostructures with desirable properties and quality. Examples of heterostructures include Si–Si$_{1-x}$Ge, GaAs–Al$_x$Ga$_{1-x}$As, GaSb–InAs and other heterostructures. Graded heterostructures are formed by many semiconductor compounds, in particular, A_3B_5 compound system.

The main property of heterostructures used in most heterostructure devices is the nonuniformity of spatial distributions of the band-gap and the edges of the valence and conduction bands. This leads to the formation of the so-called quasielectric field in heterostructure bulk affecting charge carriers, as has been pointed out in a pioneering paper by H. Kroemer [see, e.g., (1) and references therein]. The quasielectric field in graded heterostructures forces electrons and holes to move in the same direction, despite their opposite charges (Fig. 1). In heterostructures with abrupt heterojunctions, the band offsets can form potential barriers or ramps for electrons and holes, shown in Fig. 2. The band offsets are the result of abrupt variations of the chemical composition. Thus, the energy of the carriers at the band edges must change as those carriers pass through the heterojunction.

An important practical constraint is the necessity to select materials with small differences in lattice constants at the required fabrication and operating temperatures. A good lattice match is needed to minimize the density of interface states and strain fields at the heterojunction. A heterostructure with a double heterojunction can form a potential well. If such a well is narrow enough, the energy spectrum of electrons (or holes) becomes quantized (Fig. 3), due to the confinement of the latters in the direction perpendicular to the heterojunction plane. Such potential wells are known as quantum wells (QWs).

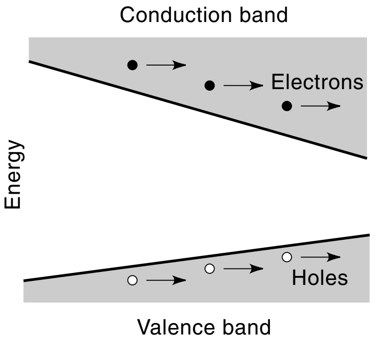

Figure 1. Forces on electrons and holes in a graded-gap heterostructure. The forces in electrons and holes are in the same direction.

Heterostructures are the elements of many of the most advanced semiconductor devices currently being developed and fabricated. They are essential parts of modern optoelectronic devices, such as semiconductor lasers, light-emitting diodes, and photodetectors with highest performance. Heterostructures are being employed increasingly in high-speed digital and high-frequency analog devices (2,3). The advantages of heterostructures are that they provide effective control over the states and motions of charge carriers—electrons and holes in active regions of heterostructure-based devices.

HETEROSTRUCTURE BIPOLAR TRANSISTORS

The principle of a bipolar transistor with heterojunctions is old as the transistor itself. A heterostructure (heterojunction) bipolar transistor (HBT) is the first semiconductor device incorporating heterostructures as it has been patented by W. Shockley as early as 1948. HBTs differ from ordinary bipolar

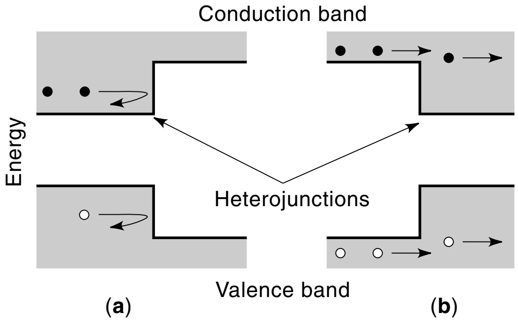

Figure 2. Energy barriers (a) and ramps (b) for electrons and holes in an abrupt heterostructure. Electrons and holes are rejected from the heterojunction if their energy is smaller than the barrier height. They acquire the energy passing the ramp at the heterojunction.

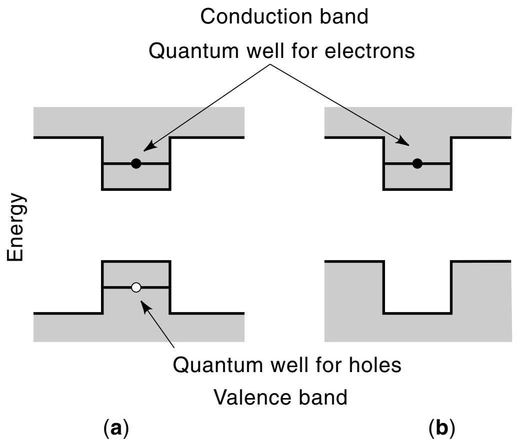

Figure 3. Quantum wells for electron and holes (a) and quantum well for electrons only (b) in double heterostructures.

transistors by the utilization of a wide band-gap semiconductor material for the transistor emitter and, in some cases, for the collector, instead of the same material as for the base. In particular, HBTs are formed by a N–p–n heterostructure with a N–p heterojunction serving as the emitter junction, and a p–n junction for the collector. Such HBTs are single heterostructure bipolar transistors, and for them the acronym SHBT is sometimes used. SHBTs can be made of P–n–p heterostructures as well. Double heterostructure bipolar transistors (DHBT) consists of both the emitter and collector heterojunctions. They have N–p–N or P–n–P structures. Symbols N and P denote the wide band-gap semiconductor portions doped by donors and acceptors, respectively, while the symbols n and p correspond to the narrow band-gap regions with related type of doping.

The basic idea of an HBT is as follows. Consider the energy band structure of an N–p–n HBT with an abrupt or graded emitter heterojunction, as in Fig. 4. The incorporation of the wide-gap emitter leads to the formation of an additional barrier for the carriers in the base (holes in the example under consideration in Fig. 4) inhibiting their escape to the emitter region. This decreases the current of holes injected from the base into the emitter. A figure of merit for an HBT is the ratio of the collector current I_c to the base current I_b:

$$\beta = \frac{I_c}{I_b} < \frac{I_n}{I_p} \equiv \beta_{\max} \tag{1}$$

Here I_n and I_p are the currents of electrons injected from the emitter into the base and holes injected from the base into the emitter. The ratio of the electron and hole currents, that is, the parameter $\beta_{\max}$, is given by the following expression:

$$\beta_{\max}^{(\mathrm{HBT})} = \frac{N_e}{p_b}\frac{v_{nb}}{v_{pe}} \exp\left(\frac{\epsilon_v}{kT}\right) = \beta_{\max}^{(0)} \exp\left(\frac{\epsilon_v}{kT}\right) \tag{2}$$

for HBTs with an abrupt emitter heterojunction and

$$\beta_{\max}^{(\mathrm{HBT})} = \beta_{\max}^{(0)} \exp\left(\frac{\epsilon_v + \epsilon_c}{kT}\right) \tag{3}$$

in the case of HBTs with a graded heterojunction. Here k is the Boltzmann constant, T is the temperature, N_e and p_b are the electron and hole concentrations in the emitter and the base, respectively, v_{nb} and v_{pe} are the mean velocities of electrons and holes in the related regions, ϵ_v and ϵ_c are the band edge discontinuities related to the valence and conduction bands in the case of an abrupt heterojunction. For a graded heterojunction, ϵ_v and ϵ_c are the fractions of the change of the band gap in the emitter and base regions related to the valence and conduction bands. In the general case $\epsilon_v + \epsilon_c = \Delta\epsilon_g$, where $\Delta\epsilon_g$ is the difference of the band gaps in the different parts of the heterostructure. In Eqs. (2) and (3) $\beta_{\max}^{(0)}$ corresponds to a homostructure bipolar transistor ($\epsilon_v = \epsilon_c = 0$), with the same doping of all its parts as the HBT under consideration.

For a good transistor, a value $\beta_{\max}$ should be large. In conventional bipolar transistors the large value of $\beta_{\max}$ is achieved by significantly higher doping level of the emitter, in comparison to the base ($N_e \gg p_b$). However, very high values of $\beta_{\max}$ can be realized in HBTs, almost regardless of the doping ratio, due to large value of the exponent in Eqs. (2) and (3). Indeed, if $\Delta\epsilon_g = 0.2$ eV at $T = 300$ K, one has $\beta_{\max}^{(\mathrm{HBT})}/\beta_{\max}^{(0)} = \exp(\Delta\epsilon_g/kT) \simeq 3000 \gg 1$. Thus, high β-values can be obtained without a high emitter-to-base doping ratio. The

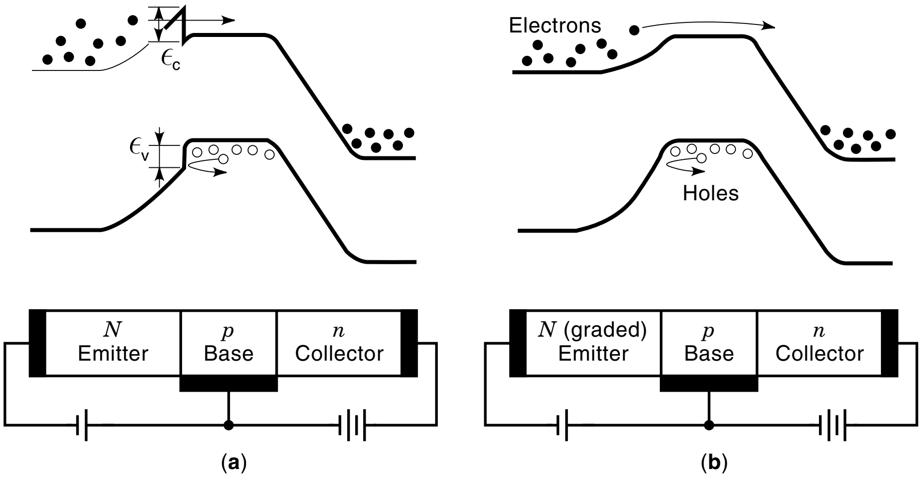

Figure 4. Energy band diagrams of N–p–n HBTs with an abrupt (a) and graded (b) emitter and schematic view of their structure.

increase of the base doping level results in lower base resistance. Simultaneously, a lightly doped emitter region provides smaller capacitance of the emitter. Both high base and low emitter doping promote better high-frequency performance of HBTs, in comparison to homostructure bipolar transistors. This is due to lower base resistance and smaller emitter–base capacitance. High base doping leads to lower noise as well. In addition, high base doping results in higher punch through voltage.

The conduction band discontinuity in the emitter hererojunction provides the injection of hot electrons from the emitter to the base. If the base is thin enough, the injected electrons can pass it without scattering or enduring a few collisions with impurities and phonons. In the case of such ballistic or near ballistic transport of electrons in the HBT base, their delay time can be very short. This also contributes to the advantages of HBTs over standard bipolar transistors. The incorporation of the graded-gap base with quasielectric field yields the acceleration of the injected electrons (or holes) in the base. Such a design provides higher performance as well.

Apart from HBTs with a single heterojunction (usually in the emitter), that is, SHBTs, DHBTs are also considered as prospective components, especially for digital circuits and novel functional devices. The utilization of an additional heterojunction (in the collector) opens up opportunities for separate optimization of the base and the collector—the interchangeability of their functions in some circuits.

The incorporation of more sophisticated heterostructures into the emitter of an HBT or its other parts can substantially extend the diversity of the HBT characteristics. For example, HBTs with a double-barrier heterostructure in the HBT emitter providing resonant-tunneling injection can exhibit N-shape current-voltage characteristics. The utilization of resonant-tunneling HBTs (RTHBT) promises a significant reduction in the logic circuits complexity (4). HBTs without base contact can be used as phototransistors with very high photoelectric gain, making them rather effective photodetectors for optical fiber communication systems and other applications.

HETEROSTRUCTURE HOT-ELECTRON TRANSISTORS

Heterostructure hot-electron transistors (HET) are made on the base of a double heterojunction structure. Wide-gap regions form the HET emitter and collector. A narrow-band-gap region, sandwiched between the wide-band-gap emitter and collector regions, serves as the HET base. In contrast to HBTs, the HET base is doped by the same type of dopants as the emitter and the collector. Hence HETs are unipolar devices. The energy band diagram of a HET with a *N*–*n*–*N* structure is shown in Fig. 5.

The electron injection from the emitter to the base, and, further, to the collector in HETs with the structure of Fig. 5, is associated with thermionic emission of electrons overcoming the barrier at the *N*–*n* interface. Electrons injected from the wide-band emitter have excess kinetic energy in the base. Their motion is directed primarily perpendicular to the heterojunction plane. The directed velocity of electrons significantly exceeds the thermal velocities of both the injected and thermalized electrons in the base. That is why such transistors are called the HETs. The thermalized (or cold) electrons provide electrical neutrality of the base. As the scattering of the injected electrons in the HET base leads to their capture in the latter, and prevents them from the injection into the collector, the electron transport in the base should be either ballistic or near ballistic.

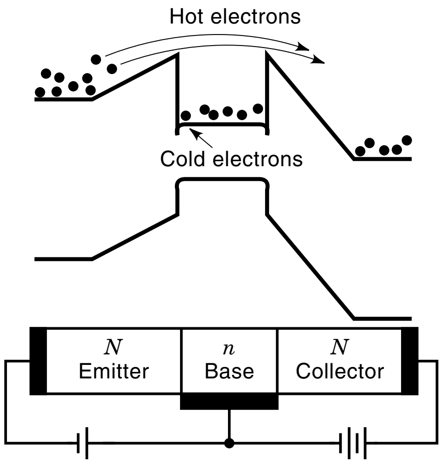

Figure 5. Energy band diagram of a *N*–*n*–*N* HET and schematic view of its structure.

Different types of HETs have been proposed [see, e.g., the article by S. Luryi (4)]. The injection of electrons (or holes in *P*–*p*–*P* HETs) from the emitter can be associated with thermionic or tunneling processes. The energy band diagram of a HET, with tunneling injection of electrons, is shown in Fig. 6.

The main problem connected with the development of high-performance HETs is the trade-off between the capture rate of hot electrons into the base, which decreases the HET current gain, and the base resistance, which limits high-speed potentials of HETs. The point is that the enhancement of the base doping level necessary for the lowering of the base resistance leads to the increase of the capture probability of hot electrons, due to the reinforcement of their scattering on donors and cold electrons.

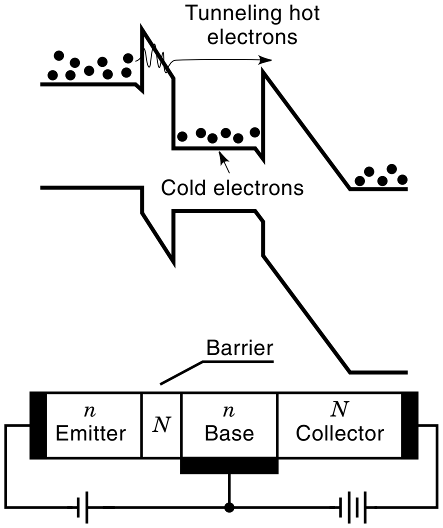

Figure 6. Energy band diagram and structure of a HET with tunneling injection of electrons.

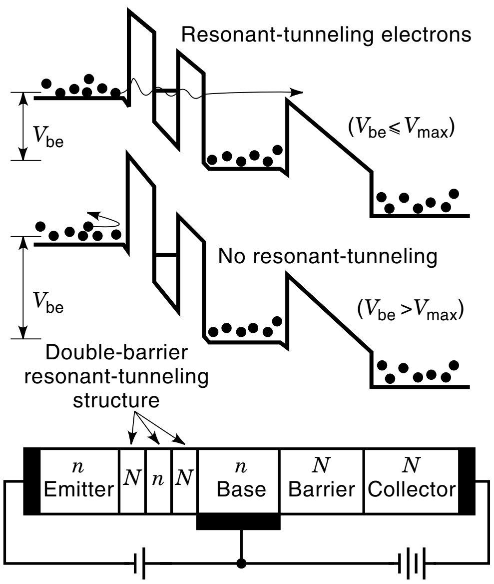

Figure 7. Operational principle and schematic view of the structure of a resonant-tunneling HET.

In HETs with a thin base, electrons in the latter can be quantized. The quantization of the electron spectrum in the HET base adds an additional complexity to the HET operation. The existence of a bound state in the electron spectrum can result in significant contribution of resonant-tunneling processes to the injection of electrons. Further development of the idea of hot electron transport resulted in the proposal of a HET with a resonant-tunneling emitter. The operation principle of resonant-tunneling HETs (RTHET) is demonstrated in Fig. 7. The most important feature of the RTHET operation is that at some collector-base voltage, the injected electron current has a maximum. The further increase of this voltage leads to a sharp drop of the injected current. Thus, RTHETs are transistors exhibiting negative differential resistance. This property is considered as very promising for future applications in different circuits.

Though HETs of different types are still under investigation, they have no commercial significance, despite very promising features of their characteristics.

HETEROSTRUCTURE FIELD-EFFECT TRANSISTORS

Heterostructure field-effect transistors (HFET) are field-effect, three-terminal devices, akin to the metal-semiconductor field-effect transistors (MESFET) with a Schottky gate and metal-insulator field-effect transistors (MISFET), taking advantage of electron transport in heterostructure channel. A general name HFET is used for a family of field-effect transistors on the base of different heterostructures. This family includes the modulation-doped field-effect transistor (MODFET), which is also known as the high-electron-mobility transistor (HEMT), the heterostructure insulated-gate field-effect transistor (HIGFET), and some others.

In MODFETs, the wide-band-gap layer beneath the metallic gate is doped, and carriers transfer to the layer of an undoped narrow-gap material. The narrow-band-gap material layer forms the MODFET channel, which is usually undoped. The result of the modulation doping is that electrons (or holes) in the channel are spatially separated from the doped layer. Because of this, they can have extremely high mobility along the heterojunction due to the elimination of impurity scattering. The most common MODFETs utilize Al$_x$Ga$_{1-x}$As –GaAs heterostructures. A typical view of the MODFET structure cross-section is shown in Fig. 8.

Electrons (holes) in the MODFET channel are confined by the heterojunction from one side and by the electric potential creating the electric field, forcing them against the heterointerface. Such confinement of electrons may lead to the quantization of their energy spectrum. If the electron confinement is strong, so that the width of the channel is small enough, electrons form a two-dimensional (2-D) electron gas, located near the heterojunction. Sometimes, MODFETs with a 2D electron gas in the channel are called the two-dimensional electron gas field-effect transistors (TEGFET).

The MODFET performance is strictly dependent on the thickness and quality of a very thin undoped layer of a wide-gap material, separating the doped region and the narrow-band-gap channel. This so-called spacer is usually made of i–AL$_x$Ga$_{1-x}$As (see Fig. 8).

HIGFETs differ from MODFETs, in that both the wide-band-gap and the narrow-band-gap layers are undoped. In some HFETs, the narrow-band-gap channel is doped. Such HFETs lose the advantage of high-electron mobility. Their operation is similar to that of MISFETs. Along with the HFETs, in which the channel is formed by a heterojunction and an electrostatic barrier, in some HFETs a double heterostructure is used to form the channel. In the latter case, the HFET channel can be a QW, because of strong electron confinement.

HETEROSTRUCTURE LASERS AND LIGHT-EMITTING DIODES

First semiconductor lasers began as homostructure devices comprising a p–n-homojunction. Today, semiconductor lasers are usually made of a heterostructure, forming a single or multiple QW. The incorporation of a heterostructure and, especially, a QW in the laser structure provides significant advantages of heterostructure laser diodes (HLD) over lasers with homojunctions (2,5,6,7). The same is true for heterostructure light-emitting diodes (HLED) as well. The main of such advantages are much lower threshold current of lasing and higher operational temperatures. The implementation of heterostructures in lasers resulted in the development and wide applications of HLDs operating at room temperature.

The energy band diagrams of HLDs are shown in Fig. 9. The wide-band-gap N- and P-regions provide the electron and hole injection into a narrow-band-gap active region (Fig. 9).

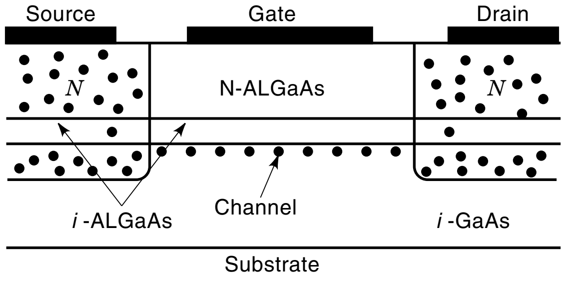

Figure 8. Cross-section view of a MODFET with n-channel.

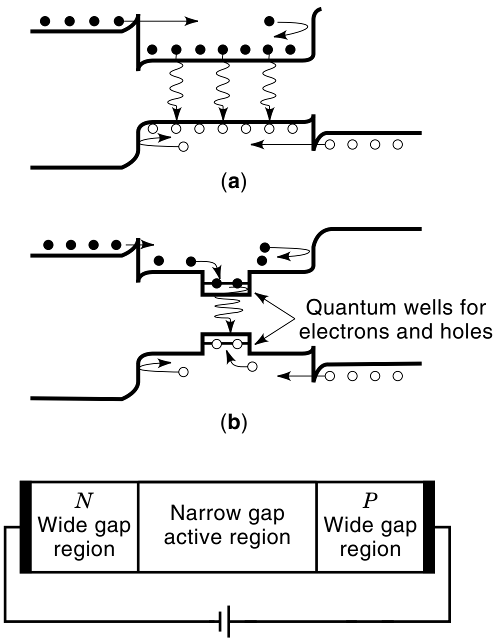

Figure 9. Energy band diagrams of HLDs with a narrow-gap active region (a) and narrow-gap active region with a quantum well (b).

The lasing power is given by the following equation:

$$P = \frac{\hbar\omega}{e}(I - I_{\mathrm{th}}) \tag{4}$$

where $\hbar\omega$ is the energy of the lasing photons, $\hbar$ is the reduced Planck constant, ω is the photon angular frequency, e is the electron charge, I is the pumping current and I_{th} is the threshold current. The latter is defined by the properties of the HLD structure materials, the HLD geometry, quality of the mirrors reflecting generated radiation or reflecting property of the HLD surfaces serving as the mirrors, and so on.

In HLDs with a QW, electrons and holes are captured in the latter and occupy 2-D states. Due to the existence of two barriers, there is the electon and hole confinement within a narrow-gap region. So the barriers prevent the leakage of carriers from the HLD active region. It results in higher electron and hole concentrations in the active narrow-band-gap region, in comparison with homostructure lasers at the same values of the injected current. It means that the threshold concentration of electrons and holes sufficient for the change of the absoption coefficient from negative (absorption of photons with the energies close to the energy gap of the active region material) to positive (amplification) is achieved at lower injected current. As a result, the injected current corresponding to the threshold of lasing (threshold current I_{th}) reduces if a double heterostructure is used. The incorporation of a more narrow-band-gap layer into the HLD active region, which forms a QW, yields an additional improvement in the laser performance. Smaller density of states in a QW, due to 2-D nature of the latter, leads to their more full occupation by electrons and holes at given value of the injected current. This effect also contributes to the achievement of the lowest possible threshold current I_{th}.

Apart from the electron and hole confinement, HLDs benefit of the confinement of lasing modes, due to the waveguide effect. This effect (named optical confinement) is connected with the larger crystal lattice refraction index of a narrow-gap part of the HLD structure playing a role of the active region. In homostructure lasers, the effect of optical confinement plays some useful role in reducing the diffraction losses of emitted radiation. In such lasers, the optical confinement is associated with the nonuniformity of the electron and hole concentrations near the p–n junction. In HLDs, the optical confinement is much more effective.

The spectrum of radiation emitted by HLDs and HLEDs is determined primarily by the value of the energy gap of the active region material. The energy of the emitting photons $\hbar\omega$ is close to the energy gap of the active region semiconductor E_g:

$$\hbar\omega \simeq E_g \tag{5}$$

Equation (5) can be rewritten as

$$\lambda \simeq \frac{2\pi\hbar c}{E_g} \tag{6}$$

where λ is the lasing wavelength and c is the velocity of light in vacuum. If E_g is expressed in electron volts, the lasing wavelength λ in micrometers according to Eq. (6) is given by $\lambda \simeq 1.24/E_g$. For HLDs with a GaAs active region (E_g = 1.42eV) and $\mathrm{Al}_{1-x}\mathrm{Ga}_x\mathrm{As}$ contact regions, one has $\lambda \simeq 0.87\ \mu$m. Utilizing different semiconductor materials, especially binary, ternary, and quaternary compounds, one may fabricate HLDs and HLEDs operating from midinfrared to blue range of the spectrum. In HLDs with QWs in the active region, the emitted photons are generated due to the transitions from the electron quantum levels to the hole quantum levels in the QWs (see Fig. 9). In such a case, the effective band gap defining the energy of the lasing photons E_g^{QW} and their wavelength $\lambda \simeq 2\pi\hbar c/E_g^{QW}$ depend also on the positions of the quantum levels, with respect to the bottom of the conduction and the top of the valence bands in the QWs. One may obtain

$$\hbar\omega \simeq E_g^{QW} = E_g + \frac{\pi^2\hbar^2}{2w^2}\left(\frac{1}{m_n} + \frac{1}{m_p}\right) \tag{7}$$

Here w is the width of the QW, m_n and m_p are the effective masses of electrons and holes, respectively. Growing the HLD structure with appropriate width of the QW in the action region, one may control the lasing wavelength.

HLDs and HLEDs find numerous applications. They are used in consumer electronics, for example, in CD players, optical communications, navigation devices, and other systems. Thanks to the development of HLDs and HLEDs, operating in relatively long-wavelength range of spectrum from one side, and heterostructure devices, emitting very short-wavelength light (blue light), their applications can be extended to atmosphere monitoring system, displays, traffic lights, and so on.

QUANTUM WELL PHOTODETECTORS

Conventional photodetectors utilize the transitions of electrons from the valence-band ground state to the conduction-band excited state. The photocarriers (electrons and holes) created due to such interband transitions produce a photocurrent in photodetectors. To create an electron-hole pair, the photon energy $\hbar\omega$ should be greater than the energy gap E_g of a semiconductor material used for a photodetector. By controlling E_g, one may fabricate photodetectors for different ranges of spectrum. It is possible by using a chemical composition chosen in proper way. For visible or near-infrared ranges of spectrum, A_3B_5 and some other semiconductor materials are used.

Carrier multiplication, which results from impact ionization initiated by electrons and holes generated due to optical interband transitions at high electric fields across the photodetector active region, is used to achieve internal photoelectric gain and, as a result, higher performance. Avalanche photodiodes (APD), which utilize impact ionization at bias near the breakdown voltage, can be built using both homo- and heterostructures. Two of the crucial performance characteristics of APDs, the gain-bandwidth product and the excess noise arising from the random nature of the avalanche multiplication of electrons and holes, are determined by the electron and hole ionization coefficients and, what is more important, by the ratio of the latter. One approach to achieving low multiplication noise in APDs is the use of heterojunctions to artificially enhance the ionization rate of either electrons or holes. The most successful APD of this type is the APD with a multiple QW structure. The point is that, for low-noise and high gain-bandwidth product, the ratio of the electron and hole ionization coefficients k should be either large or small ($k \ll 1$ or $k \gg 1$). It means that a large difference in the ionization rates is necessary. As electrons emerge from the wide-band-gap region between the QWs into the narrow-band-gap portion (into the QW), the discontinuity in the conduction band provides sufficient additional energy to initiate ionization. This enhances the ionization rate of electrons. The ionization rate for holes, on the other hand, is not enhanced to the same degree, since the valence band offset is smaller than that of the conduction band (2,8) in many practically important heterostructures.

Heterostructure APDs with QWs are successfully fabricated in GaAs–$Al_{1-x}Ga_xAs$ and InP–$In_{0.53}Ga_{0.47}As$ compound material systems, and some others.

To satisfy the condition $\hbar\omega > E_g$ for very important far- and mid-infrared ranges of spectrum, corresponding to wavelengths $\lambda = 2\ \mu m$ to $20\ \mu m$, semiconductor alloys like $Hg_{1-x}Cd_xTe$ are used. There are substantial technological difficulties to grow, process, and fabricate photodetectors made of such materials. The transitions from the impurity states to the conduction or valence band can be also utilized in photodetectors operating in far- and near-infrared ranges. However, these photodetectors have also some disadvantages.

Quantum well intersubband photodetectors (QWIP), based on semiconductor heterostructures, are considered as a very prospective alternative to both $Hg_{1-x}Cd_xTe$ interband photodetectors, as well as impurity photodetectors. QWIPs utilize the intraband electron transitions in the conduction band (in n-type QWIPs) or the intraband hole transitions in the valence band (in p-type QWIPs). By absorbing photons, electrons transfer from the bound states in QWs into states above the barriers between the QWs (continuum states), that is, they transfer between the subbands within a band. Such intersubband transitions result in the occurrence of electrons (holes) in continuum states, where they can freely move, producing a photocurrent. Conventional QWIP consists of a heterostructure with a single or multiple QW, doped either by donors or acceptors. The QW structure is supplied by contact regions of the same type of doping as the QWs. These contacts serve as the QWIP emitter and collector (9). The conduction band edge profile of the QWIP structure is shown in Fig. 10. Usually QWIPs are made of A_3B_5 or $Si_{1-x}Ge_x$ compounds.

QWIPs operate in the range of spectrum, in which the energy of incident photons is sufficient to provide electrons absorbing such photons energy to escape from a QW:

$$\hbar\omega > E_i \tag{8}$$

Here E_i is the ionization energy of the QW, which is the difference between the energy of the barrier top and the bottom of the 2-D subband in the QW (see Fig. 10). The ionization energy E_i depends on the depth of the QW which, in turn, is defined by the difference in the chemical compositions of the barrier and QW materials, and the QW width. Both the depth and width can be easily varied during the QWIP structure growth process, to adjust the range of the sensitivity of the QWIP.

The photoexcited electrons are collected, thereby producing a photocurrent. The escape of electrons from QWs due to their photoexcitation leads to some redistribution of the potential across the QWIP structure and, in turn, to the increase of the electric field at the QWIP emitter contact. This results in the injection of extra electrons from the emitter. The current created by the injected electrons can significantly exceed the current produced by the photoexcited electrons, so that QWIPs can exhibit a photoelectric gain. The latter can be markedly greater than unity. The photocurrent in a QWIP is given by the following formula:

$$I_{\text{ph}} = \frac{e\sigma\Sigma\Phi}{p_c} \tag{9}$$

Here σ is the cross-section of the electron photoionization from the QW, Σ is the electron sheet concentration in each QW defined by the sheet concentration of donors, Φ is the photon flux, and p_c is the probability of the electron capture into QWs. It is instructive that the photocurrent according to Eq. (9) does not depend on the number of QWs in the QWIP N. Usually the value p_c is small, so that the photoelectric gain $g = (Np_c)^{-1}$ can be large, even in QWIPs with multiple QW

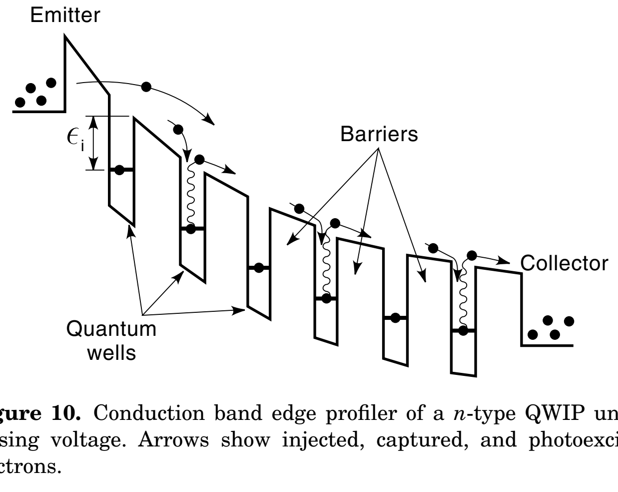

Figure 10. Conduction band edge profiler of a n-type QWIP under biasing voltage. Arrows show injected, captured, and photoexcited electrons.

structure. From Eq. (9), one may obtain the following expression for the QWIP responsivity:

$$R = \frac{e\sigma\Sigma}{p_c\hbar\omega} \tag{10}$$

For a QWIP with typical parameters $\sigma = 2 \times 10^{-15}$ cm^2, $\Sigma = 10^{12}$ cm^{-2}, $p_c = 0.01$ to 0.05, and $\hbar\omega = 0.1$ eV ($\lambda \simeq 12$ μm), from Eq. (10), one has $R = 0.4$ to 2 A/W.

Relatively simpler and cheaper QWIP technology is not the only advantage making QWIPs potential competitors to standard infrared photodetectors. The QWIP advantages are connected also with their intrinsic high-speed operation and the feasibility of their integration with other A_3B_5 and $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ devices.

Despite the novelty of QWIPs, they already find applications as components for infrared imaging devices with large staring arrays of QWIPs.

OTHER HETEROSTRUCTURE DEVICES

Among heterostructure devices not discussed above, there are some others that are considered as very prospective in future. One may point out the real-space-transfer transistors (RSTT) utilizing the real-space transfer of electrons or holes between two semiconductor materials. The RSTT operation requires a heterostructure in which the semiconductor layer with wider energy gap has much reduced mobility. The GaAs–$\mathrm{Al}_{1-x}\mathrm{Ga}_x\mathrm{As}$ heterostructures have largely been used so far for the RSTTs. For detailed discussions on RSTTs, readers are referred to (4).

Solar cells are also an example of devices in which the utilization of heterostructures provides marked advantages. The advantages of heterostructure solar cells (HSC) over conventional p–n-homojunction SCs are as follows (5): First, HSCs exhibits enhanced short-wavelength response, if the energy gap of the HSC wide-band-gap layer exceeds the energy of photons to be absorbed inside the depletion region in the narrow-band-gap portion. Apart from this, they have lower series resistance, if the wide-band gap region is heavily doped without affecting its transparency. In addition, HSCs can exhibit higher radiation tolerance.

Many of novel devices utilize quantum properties of electrons in heterostructures with QWs. As an example, one may mention resonant-tunneling diodes (RTDs) for logic and ultra high-frequency applications (2,10). Combining RTDs with HBTs or HFETs allows the fabrication of compact high-speed circuits that operate at room temperature. Recently, the electron intersubband transitions were utilized for laser generation of mid-infrared radiation in QW structures, called the quantum cascade lasers (11). The intersubband lasers have many potential applications in the mid-infrared range of spectrum.

The integration of heterostructures utilizing both intersubband (intraband) and interband transitions open up additional prospects for the development of new functional QW devices. For example, integrated QWIP-LED devices (12) can be used for effective conversion of far- or mid-infrared signals or images into near-infrared or, possibly, visible signals and images. In QWIP-LED devices, their QWIP part, utilizing intersubband electron transitions, serves as an element sensitive to infrared radiation. It produces a photocurrent which, being injected into the LED active region, results in the generation of relatively short-wavelength output radiation, due to radiative recombinations of the injected electrons. High-performance discrete devices and pixelless imagers can be fabricated using integrated QWIP-LED heterostructures.

In QWs electrons or holes are spatially confined in one direction. The energy corresponding to their motion in this direction is quantized, while in other directions it can be considered as classical one. Advances in microfabrication technology now permit the building of heterostructures, in which electrons and holes are confined in two or even three directions. In the first case, electrons and holes are confined in a narrow-band-gap semiconductor material region extensive in one direction and buried in a wide-band-gap material. In such heterostructures, usually called the quantum wires (QWR), the electron (hole) energy spectrum is characterized by two discrete quantum numbers and one continuous quantum number. The latter is the electron (hole) momentum. Thus, electrons and holes in QWRs are propagating as one-dimensional particles. If the region of a narrow-band-gap semiconductor, material has a form of a small “box” electrons, and holes in the narrow-band-gap box exhibit fully discrete energy spectrum. Small boxes of a narrow-band-gap semiconductor surrounded by a wide-band-gap material with discrete energy spectrum are called the quantum boxes or quantum dots (QD). QDs are similar to real atoms, because electrons (holes) in them have discrete energy spectrum as it takes place in atoms. A QD is said to be a zero-dimensional structure. However, sizes of QDs are substantially larger than those of real atoms. This is due to large number of atoms of semiconductor material involved in forming of a QD. The energy spectrum of a QWR or a QD is defined by the difference in the energy gaps of the QWR or QD material from one side, and surrounding material from another. The most crucial are the QWR or QD sizes. If the QD size is small enough, the QD can have the only one quantum level. Usual size of QWRs (in the direction perpendicular to the direction of classical electron or hole motion) and QDs is about a few nanometers. Due to energy spectra significantly different from those for conventional heterostructures and even for QWs, the one- and zero-dimensional structures comprising QWRs and QDs are very promising for electronic and optoelectronic devices, especially lasers. More detailed description of the QWR and QD properties, and their possible applications, can be found in (2,13).

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