New Quantum Photoconductivity and Large Photocurrent Gain by Effective-Mass Filtering in a Forward-Biased Superlattice *p-n* Junction

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We report a new quantum-type photoconductivity in a forward-biased p^+-n junction with a superlattice in the n layer. This novel phenomenon is characterized by several striking features: a high photocurrent gain ($\simeq 7\times10^3$), accompanied by a blue shift in the spectral response and a reversal in the direction of the photocurrent, when the forward bias exceeds the built-in potential. Photoconductive gain is caused by the large difference in the tunneling rates of electrons and holes through the superlattice layers, due to their large mass difference (effective-mass filtering). This is the first time that photoconductive gain is observed in a p-n junction.

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Photoconductivity is a widespread phenomenon in semiconductors. If the lifetime of the photogenerated carriers exceeds their transit time, photoconductivity is accompanied by current gain.[1] The gain and associated gain-bandwidth product are therefore controlled by bulk properties such as carrier mobilities and lifetimes. In this Letter we report a new photoconductivity of quantum mechanical origin, accompanied by a very large photocurrent amplification, in a forward-biased superlattice p-n junction.

The heterostructure, grown by molecular-beam epitaxy, consists of a p^+-n junction grown on a 1-μm-thick n^+ ($=2\times10^{18}$ cm^{-3}) $Ga_{0.47}In_{0.53}As$ buffer layer, lattice matched to a ⟨100⟩ n^+ InP substrate. The undoped n layer ($n=1\times10^{15}$–1×10^{16} cm^{-3}) comprises 100 23-Å-thick $Al_{0.48}In_{0.52}As$ barriers alternated with 100 49-Å-thick $Ga_{0.47}In_{0.53}As$ wells. Transmission-electron-microscopy studies indicate that the interfaces are abrupt to better than two monolayers. The top p^+ region is 1 μm thick and doped to $\simeq 2\times10^{18}$ cm^{-3}. The mesa diodes (area $=1.3\times10^{-4}$ cm^2) had excellent forward and reverse I-V characteristics. From capacitance-voltage measurements the carrier concentration (n-type) in the superlattice region was found to decrease monotonically from 2×10^{16}/cm^3 (at a distance of 0.2 μm from the p^+-n heterointerface) to 4×10^{14}/cm^3 near the interface with the n^+ layer. The built-in potential determined from both C-V and I-V measurements is 0.65 V. The optical power incident on the detector was kept low ($\simeq 1$ nW); the short-circuit photocurrent was measured by a 181 PAR current-sensitive preamplifier followed by a 5604 PAR lockin.

Figure 1 shows the responsivity (photocurrent/ divided by incident optical power) at 70 K as a function of forward bias voltage at a wavelength of 1.2 μm and a chopping frequency of 1 kHz. The responsivity exhibits a relatively flat portion at low bias and then a rapid (roughly exponential) falloff at voltages greater than 0.4 V. This represents the standard behavior of the photocollection efficiency in forward-biased p-n junctions.[2] The responsivity reaches a minimum at a forward bias equal to the built-in potential (0.65 V). Above this voltage the responsivity takes off rapidly and increases by about five orders of magnitude within 0.2 V, indicating the presence of a current gain mechanism. The highest measured responsivity is 400 A/W at 0.85 V. An estimated 6% of the incident pho-

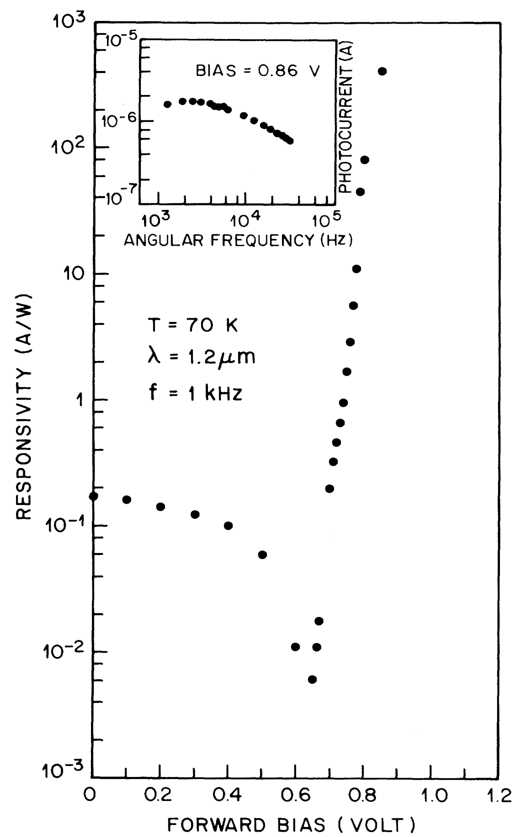

FIG. 1. Responsivity as a function of forward-bias voltage at $\lambda=1.2$ μm and $T=70$ K. The inset shows the frequency response of the structure in the high-photoconductive-gain region (0.86 V bias).

tons are absorbed in the GaInAs cladding layers and $\simeq 60\%$ in the superlattice at $\lambda = 1.2\ \mu m$. Only photocarriers generated in the latter region undergo photoconductive gain (as discussed further on in the text), so that the effective external quantum efficiency is 0.06. From this value and the measured responsivity at 0.85 V we estimate a current gain of $\simeq 7\times10^3$. The inset of Fig. 1 gives the frequency response at 0.86 V bias, obtained by varying the light-chopping frequency. The 3-dB bandwidth is $\simeq 10^4$ Hz which is equivalent to a response time $\simeq 6\times10^{-4}$ sec.

This is the first time that photoconductive gain has been observed in a p-n junction. It is accompanied by two other striking effects not previously observed: (a) The direction of the photocurrent is reversed for forward biases greater than the built-in voltage ($=0.65$ V); (b) a large blue shift in the spectral response is observed at voltages ≥ 0.65 V.

Figure 2 illustrates the spectral response of the p-n junction at zero bias, slightly before the onset of current gain (0.6 V), and in the high-gain region (0.85 V). The optical gain [= (external quantum efficiency) $\times$ (current gain)] is given by $G_0 = (h\nu/e)R$ where $h\nu$ is the photon energy, e the electronic charge, and R the responsivity at the optical frequency

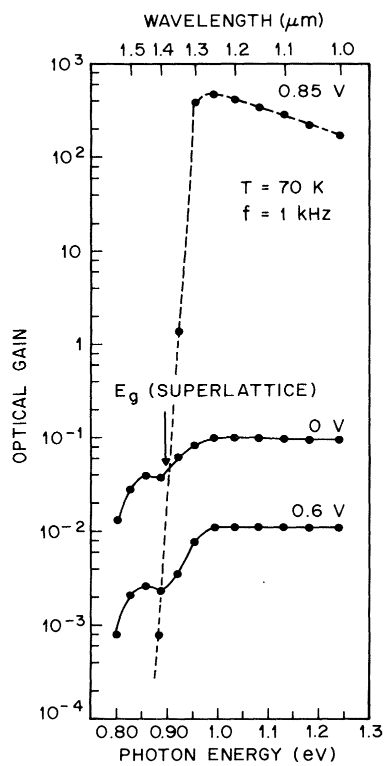

FIG. 2. Spectral response of the structure at different forward biases (0, 0.6, and 0.85 V). The optical gain is the external quantum efficiency times the current gain. The arrow indicates the calculated superlattice band gap.

ν. The zero-bias curve exhibits two regions. The low-energy cutoff (0.8 eV) corresponds to the band gap of $Ga_{0.47}In_{0.53}As$ at 70 K. For photon energies between 0.8 and 0.88 eV the photocurrent is due to minority carriers (electrons) photogenerated in the top p^+ $Ga_{0.47}In_{0.53}As$ layer and diffusing into the superlattice. The resulting efficiency is obviously only a few percent in this region. Above 0.9 eV there is a steplike increase in the photoresponse corresponding to the onset of the absorption in the superlattice, i.e., to photoexcitation from the heavy-hole miniband to the ground-state electron miniband. This transition defines the superlattice band gap. The calculated value of this gap, indicated by the arrow, was obtained by adding to the $Ga_{0.47}In_{0.53}As$ bulk band gap (0.79 eV at 70 K) the energies of the bottom of the ground-state electron and hole minibands (90 and 20 meV, respectively).[3] For the conduction- and valence-band discontinuities, the experimental values $\Delta E_c = 0.5$ eV and $\Delta E_v = 0.23$ eV were used.[4] Good agreement with the experiment is observed. The spectral shape remains the same for voltages smaller than the built-in potential, while above 0.65 V the low-energy shoulder disappears (blue shift) and the spectral response cuts off at the superlattice gap. This behavior is clearly illustrated in Fig. 2 by the two representative spectral response curves, one at 0.6 V and the other in the high-current-gain region, at 0.85 V.

It was found that at room temperature the photocurrent falls off monotonically with forward bias and no sign reversal and current gain is observed. The reversal in the direction of the photocurrent, accompanied by amplification, starts to be observed at temperatures $\lesssim 150$ K. The optical gain then increases with decreasing temperature down to 70 K. At lower temperatures (10 K) the optical gain was comparable to that at 70 K.

Finally p^+nn^+ structures with $Al_{0.48}In_{0.52}As$ in the n region, in place of the superlattice, and $Ga_{0.47}In_{0.53}As$ p^+, n^+ layers were also tested. The photocurrent as function of forward bias reached a minimum and then increased again after reversing direction, similarly to what occurs in the structures with superlattices, but the responsivity never surpassed the zero-bias value. Thus the photocurrent reversal appears to be associated with the center layer's being of larger band gap than the two cladding layers, while the high-current gain is directly related to the presence of the superlattice.

The above phenomena can be understood by consideration of the band diagram of the structure [Fig. 3(a)]. For simplicity of illustration the band bending in the center n layer has been neglected. At zero bias [Fig. 3(a)], the built-in electric field is responsible for the drift and collection of carriers. When a forward bias is applied majority carriers are injected from the p^+ and n^+ regions and the built-in field is reduced. Both effects enhance the recombination of photogen-

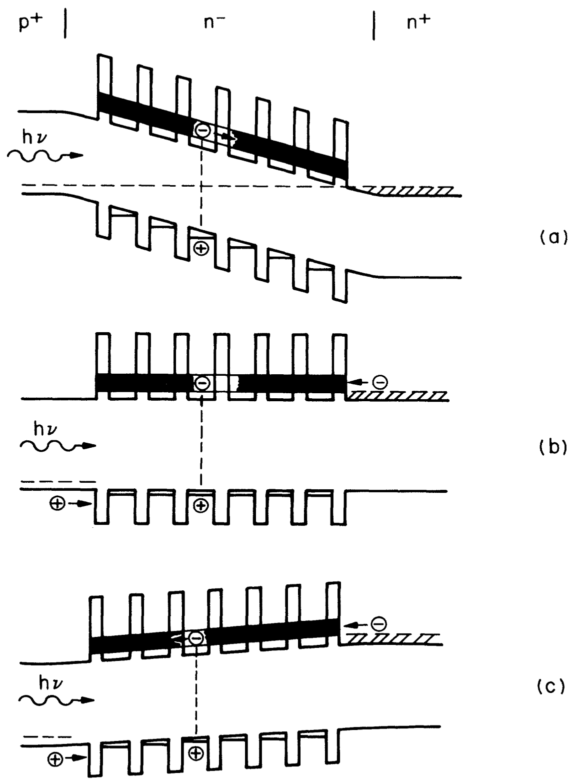

FIG. 3. Schematic energy-band diagram of the superlattice p-n junction (a) in equilibrium, (b) at a forward-bias voltage equal to the built-in potential (flat band), and (c) beyond flat band. Shown also is the effective-mass filtering mechanism.

erated carriers, so that the collection efficiency and the resulting responsivity decrease with increasing forward-bias voltage (see Fig. 1).[2] In a homojunction or a conventional double heterojunction structure (where the center layer has a smaller gap than the adjacent layers) at most one can obtain a flat band condition when the forward bias equals the built-in voltage. When this is achieved the injected dark current is extremely high and prevents the change from going beyond flat band. Any further increase in the applied bias will result in a voltage drop across the diode series resistance or in the damage of the diode.

It should be realized, however, that this is not the case for a double heterojunction structure like ours where the center layer has a wider gap than the adjacent layers. When the flat band condition is reached [Fig. 3(b)], there are still relatively large remaining barriers to the injection of electrons and holes, given by the band discontinuities of the $Al_{0.48}In_{0.52}As$/$Ga_{0.47}In_{0.53}As$ heterojunction. These barriers limit the forward dark current to values significantly smaller than in the opposite type of heterojunction, especially at low temperatures. This means that it is possible to apply a voltage greater than the built-in voltage, which will result in an electric field opposite to the original built-in field. The direction of motion of the photocarriers will then be reversed [Fig. 3(c)]. This explains the change in the sign of the photocurrent for bias voltages greater than the built-in potential. The other important point to realize is that beyond flat band [Fig. 3(c)] electrons (holes) drift in the same direction as the electrons (holes) injected from the contact regions; in other words, the photocurrent has the same direction as the dark current. Thus one can observe photoconductivity and photoconductive current gain.

The blue shift in the spectral response is explained with the aid of Fig. 3. For voltages smaller than the built-in potential, minority carriers photoexcited in the $Ga_{0.47}In_{0.53}As$ layers can reach the superlattice region by diffusion, where they are collected by the electric field, giving rise to the low-energy shoulder ($\lesssim 0.9$ eV) of the spectral response. When the electric field in the superlattice reverses direction [Fig. 3(c)], it opposes the collection of the photogenerated minority carriers and the low-energy tail of the spectral response disappears.

The large photocurrent amplification effect observed in the presence of the superlattice represents a new quantum-type photoconductivity (effective-mass filtering) and may be explained by analysis of perpendicular carrier transport.

In a superlattice the quantum states of the coupled wells broaden into minibands (extended Bloch-type states) if the mean free path λ of the carriers appreciably exceeds the superlattice period.[5] Perpendicular transport proceeds then by miniband conduction. This condition on the mean free path, however, is not always satisfied as a result of a variety of reasons. Intralayer and interlayer thickness fluctuations and alloy disorder cause fluctuations of the energies of the quasieigenstates of the wells.[6,7] If this nonhomogeneous broadening exceeds the intrinsic miniband width, Bloch states cannot be formed and the mean free path becomes equal to the superlattice period d.[6] Even in an ideal superlattice without structural imperfections or disorder, if the collision broadening due to phonon scattering is greater than the miniband width, there are no Bloch states.[6] In summary, if $\lambda \lesssim d$ the states of the superlattice become localized in the wells along the direction perpendicular to the layers and conduction proceeds by phonon-assisted tunneling (hopping between adjacent wells).[6,8] In our superlattice the calculated[3] width of the electron ground-state miniband is 30 meV and is greater than the combined compositional nonhomogeneous broadening due to the fluctuations and collision broadening due to phonons ($\simeq 10$ meV). Electron transport perpendicular to the layers occurs, therefore, by miniband conduction.

The situation is very different for holes. The ground-state heavy-hole miniband is only 0.7 meV wide, which is much smaller than nonhomogeneous and collisional broadening. Thus, holes are localized perpendicular to the layers and are transported by hopping between adjacent wells. The hopping mobility for holes is orders of magnitude smaller than the electron mobility. This is mainly the consequence of the large effective-mass difference. Photogenerated holes therefore remain relatively localized (their hopping probability is negligible) while photoelectrons and those injected by the n^+ contacts are transported through the superlattice by miniband conduction [Fig. 3(c)] (effective-mass filtering). This produces a photoconductive gain given by the ratio of the electron-hole pair lifetime τ (which defines the response time of a photoconductor) to the electron transit time $t_e(=L/\mu_e F)$.

The mobility μ_e decreases exponentially with increasing barrier thickness, a manifestation of the tunneling nature of transport.[9] This explains the strong decrease in the observed photocurrent amplification as the superlattice barriers were made thicker.

From the interpretation of the observed photocurrent amplification we expected to observe a large photoconductive gain by effective-mass filtering at small voltages also in n^+in^+ photoconductors with a superlattice in the i layer. These structures were structurally identical to the $p^+n^-n^+$ diodes previously tested except that both $Ga_{0.47}In_{0.53}As$ cladding layers are now n^+. An extremely large current gain ($\simeq 2\times10^4$ at 0.2 V) was observed and detailed investigations conclusively confirmed the effective-mass filtering mechanism.[10]

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