Demonstration of dual gain mechanism in an InGaAs/InAlAs superlattice photodiode

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(Received 22 December 1986; accepted for publication 27 February 1987)

A high-gain photodiode in which the internal gain can result from either potential barrier lowering or mass filtering action, depending on device geometry and bias conditions, is proposed and demonstrated. The photodiode structure is similar to a modulated barrier diode and uses $In_{0.53}Ga_{0.47}As$ and InGaAs/InAlAs superlattice absorption regions. The superlattice helps to reduce the dark current and aids in mass filtering. The devices reported here were made with multilayered InP-based materials grown by molecular beam epitaxy and exhibit responsivity as high as 1000 A/W.

For many applications, it is desirable to be able to detect very low signal levels with moderate or low response speeds. It is also sometimes important in such applications to have a high responsivity over a large voltage range. We present here the results obtained from a heterojunction photodiode, which can, in principle, exhibit large internal gains by two different mechanisms, depending on the device design, temperature of operation, and applied bias. These mechanisms are enhanced thermionic emission over a potential barrier[1,2] and effective mass filtering,[3] which can separately, or in combination, give rise to large gains over a wide voltage range. The device being reported here exhibits a peak responsivity of 140 A/W at 300 K and ~1000 A/W at 50 K in the spectral range of 1.25–1.55 μm.

The operating principles of our devices are briefly described, with respect to the band diagrams shown in Fig. 1. The device is biased such that the InGaAs layer is positive with respect to the superlattice (SL). If the photoexcitation is incident on the InGaAs side, and is mostly absorbed in this ternary layer, the photogenerated holes drift toward the barrier layer and accumulate there, thereby lowering the barrier height. This results in increased thermionic emission of electrons from the SL to the ternary layer and consequent optical gain. On the other hand, if the device is excited from the SL end, electron-hole pairs are mostly generated in this region. Due to the bias polarity and due to increased confinement and scattering of holes in the quantum wells, all of them may not reach the barrier, and hence efficient barrier lowering may not be achieved. This agrees with our experimental observations. If the total bias and the doping and thickness of the individual layers can be so adjusted such that a combination of the potential drop across the SL and the barrier lowering can tilt its bands in the opposite direction, then photoelectrons will drift in the same direction as the electrons injected from the contact regions. The thicknesses of the wells and barriers of the superlattice are properly chosen, such that electrons are transported by miniband conduction while holes are localized in the wells along the direction perpendicular to the layers and their conduction proceeds by phonon-assisted tunneling. This is essentially an effective mass filtering effect in the SL which can yield a high photoconductive gain $G = \tau/t_r$ (τ = hole lifetime, t_r = electron transit time) over and above modulated barrier gain. Hence the structure we propose and demonstrate can, in principle, achieve high internal gains by either or both mechanisms.

The devices being reported here were grown by molecular beam epitaxy on S-doped n^+-InP substrates. The n^+-n-p^+-n-n^+ structure is essentially similar to earlier reported modulated barrier[4,5] or Camel[6] diodes, with some essential differences. The entire structure is grown with InP-based materials, and one side of the diode contains a superlattice region. The n-InGaAs and superlattice regions are undoped, with an effective electron density of 5×10^{15} cm^{-3}. The p^+ barrier layer has a hole concentration of 5×10^{18} cm^{-3} and is 80 Å thick. The thickness of the undoped regions is kept small (0.4–0.6 μm) to ensure full depletion at thermal equilibrium. The superlattice is characterized by $L_Z = 49$ Å and $L_B = 23$ Å.

Circular mesa diodes were fabricated by etching with $1H_2SO_4$:$1H_2O_2$:$8H_2O$ (1.5 μm/min) through photolithographic masks. Au/Ge contact pads were formed by evaporation and alloying and were delineated by standard lift-off techniques. Typical diode areas were $\sim 5\times10^{-4}$ cm^2 and the zero-bias capacitance was ~1.0 pF. Typical current-voltage characteristics in the dark and under illumination are shown in Fig. 2. Using the thermionic emission model up to a bias of 2 V, a linear plot of ln I vs V is obtained from which a barrier potential of 0.6 eV is calculated. This is comparable to a value of 0.56 eV measured in GaAs/AlGaAs devices.[4] We also made homojunction devices with $In_{0.53}Ga_{0.47}As$,

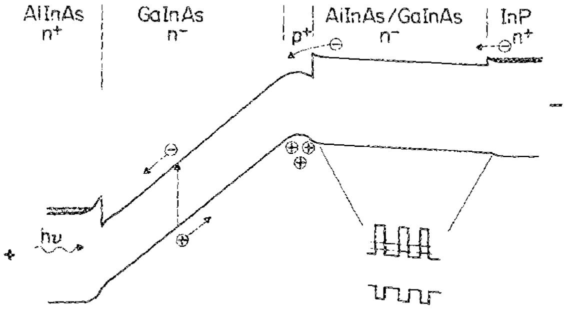

FIG. 1. Band diagrams of an n-p^+-n^- barrier diode under bias. The structures used in this study were grown by molecular beam epitaxy.

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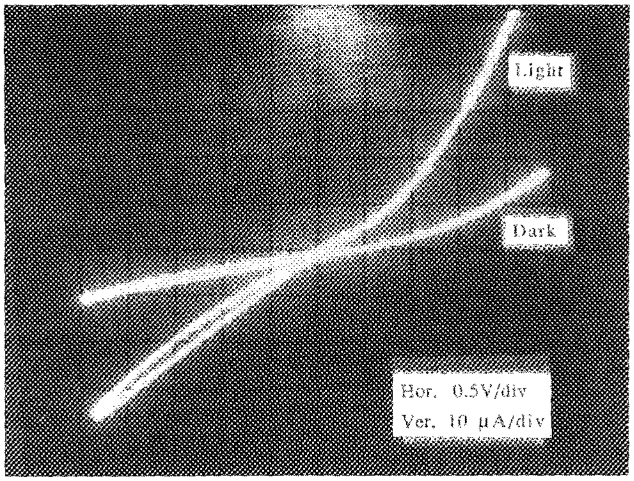

FIG. 2. Current-voltage characteristics in an InGaAs/InAlAs SL modulated carrier photodiode in the dark and under illumination.

but the leakage current in such devices reached untolerable limits. The incorporation of the SL dramatically reduced this leakage, because of the increased band gap and the achievement of material quality enhancement.[7]

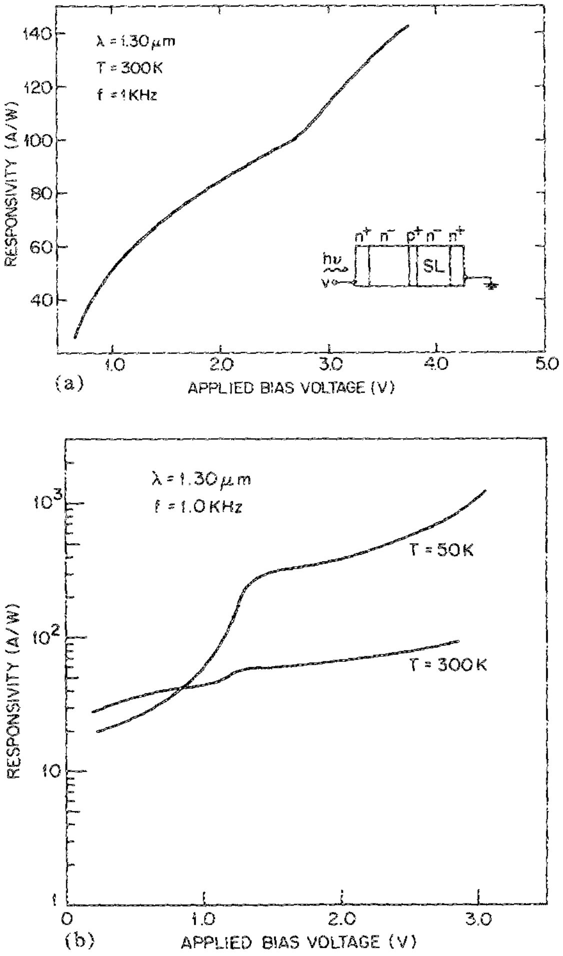

FIG. 3. Variation of responsivity with applied bias (a) at 300 K and (b) at 300 and 50 K in different samples.

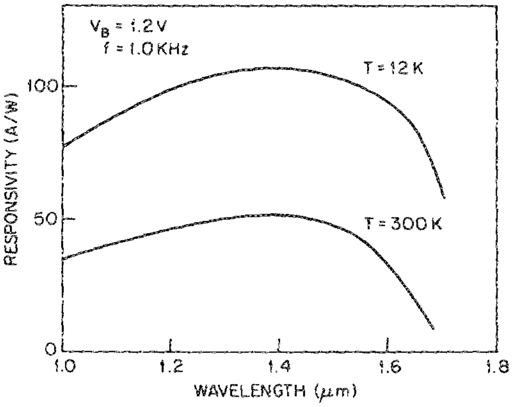

FIG. 4. Spectral response of the photodiode at 300 and 50 K.

The variation of responsivity as a function of bias and temperature in a device (sample A) which has a 0.55 μm and 0.4 μm InGaAs and SL regions, respectively, is shown in Fig. 3. The 1.3 μm photoexcitation is principally absorbed in the InGaAs layer and the bias configuration is as shown in Fig. 1. At room temperature the responsivity increases with bias [Fig. 3 (a)] because of barrier lowering due to a more efficient accumulation of holes in the barrier layer. As the bias is further increased, the band bending in the superlattice region is reduced and this prevents the accumulation of holes in the barrier region. Therefore, a saturation occurs in the characteristics around 2.5 V. Beyond this bias value there is a second region where the responsivity increases with bias. We believe that effective mass filtering between electrons and holes may be responsible. Figure 3(b) depicts the gain at 300 and 50 K in another sample (b). It is clearly seen that the gain decreases at low biases, which would be true for thermionic emission, and increases at higher biases, confirming mass filtering in this bias range. Furthermore, the measured gains are extremely high and comparable to those reported by Capasso.[3] The kink in the low-temperature responsivity characteristics is not clearly understood and we think this may be a heterostructure effect. It should also be noted that the data of Figs. 3(a) and 3(b) were obtained with extremely low light intensities ($\sim \mu$W). Figure 4 depicts the temperature-dependent spectral response at 1 V bias with illumination from the InGaAs layer end. The long wavelength cutoff represents the absorption edge of the ternary material and the decrease in responsivity at shorter wavelengths is mainly due to surface absorption effects. The peak response is obtained in the 1.25–1.55 μm range and this is representative of absorption in both ternary and superlattice regions.

In conclusion, we have reported the principle and operation of a high-gain photodetector in which a high responsivity can result from two independent internal gain mechanisms which complement each other. We have used an InGaAs/InAlAs SL in one region of an InGaAs modulated barrier photodiode. The SL not only helps to reduce the reverse leakage current, but with the proper band tilting, can give high photoconductive gains by a mass filtering action.

The authors acknowledge stimulating discussions with Professor H. Beneking and Dr. F. Capasso. The work is being supported by the Defense Advanced Research Projects Agency and the Army Research Office under contract DAAL03-86-K0105.

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