Resonant cavity enhanced AlGaAs/GaAs heterojunction phototransistors with an intermediate InGaAs layer in the collector

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Gain and spectral response of heterojunction phototransistors (HPTs) having a thin (0.1 μm) InGaAs strained absorbing layer in the collector has been investigated. Low dark current ~ 5 pA (1×10^{-8} A/cm^2) and large optical gain as high as 500 were observed. A resonant cavity composed of an AlAs/GaAs buried mirror structure (reflectivity $R = 0.9$) and the epilayer surface ($R = 0.3$) was used to enhance the otherwise small quantum efficiency η (at InGaAs absorption wavelength). For a 1000 Å absorbing layer an improvement of η from 6.7 to 43% (6.4-fold) was demonstrated, in agreement with calculations, through the spectral analysis of the HPTs with and without resonant cavities.

Heterojunction phototransistors (HPTs) are promising candidates as high-gain infrared detectors for fiber-optic communication.[1-4] Unlike avalanche photodiodes, HPTs can provide high optical gain without excess noise due to avalanching. The optimum HPT designs reported earlier[5,6] suggest that the absorption in the emitter and the base regions should be minimized in order to maximize the gain. This optimization can be accomplished by the insertion of a thin, direct band-gap material such as InGaAs in the collector region of an AlGaAs/GaAs HPT. The photosensitivity will be limited by the small critical thickness of the lattice-mismatched material. To achieve reasonable quantum efficiencies, a thick active layer and antireflection coating is desirable ($\eta = 63\%$ for 1 μm thickness). However, reduced device speed results from longer transit times in the thick depletion region. It is desirable to enhance the quantum efficiency without increasing the collector thickness with the resultant improvement in the gain-bandwidth product. This enhancement was achieved by the novel approach presented here: integrating a HPT with an InGaAs intermediate collector layer into a resonant cavity as shown in Fig. 1. The resultant resonant cavity enhanced HPT (RCE-HPT) exhibits high photosensitivity at resonant wavelengths and rejects the antiresonant wavelengths. The device demonstrated here possesses a high quantum efficiency (43%) for only a 1000 Å InGaAs absorption region and a very high optical gain of more than 500.

By introducing the InGaAs layer, the photosensitivity spectrum extends to longer wavelengths ($\geqslant$9000 Å) where the absorption in the base and the heavily doped GaAs collector is negligible. Thus, eliminating the absorption in the subcollector, i.e., diffusion current component, may improve the high-frequency performance of the HPT. Furthermore, having a lossless structure, except the thin active region in the collector, enables the formation of high quality factor Q cavity, which strongly enhances the quantum efficiency of the phototransistor at resonant modes. Therefore, this RCE-HPT provides wavelength selective and high-speed detection, in addition to high sensitivity, which may also be useful in frequency division multiplexing (FDM) communication systems.

The investigated devices were grown by molecular beam epitaxy (MBE). The growth was initiated with a 0.5 μm n^+-GaAs buffer layer. On some of the devices, an AlAs/GaAs quarter-wave stack as a high-reflectivity mirror ($R = 0.9$, center wavelength $\approx$9500 Å) was grown prior to 0.5 μm n^+ subcollector. Then, the collector consisting of 0.4 μm n-GaAs ($n = 5\times10^{16}$ cm^{-3}) and 0.1 μm undoped In$_{0.05}$Ga$_{0.95}$As layers was grown. This was followed by a p-GaAs base (0.1 μm, $p = 5\times10^{17}$ cm^{-3}) and a n-Al$_{0.3}$Ga$_{0.7}$As emitter (0.2 μm $= 5\times10^{17}$ cm^{-3}). Finally, a 0.1 μm AlGaAs and a 500 Å GaAs cap layers (both $n = 5\times10^{18}$ cm^{-3}) were grown. Standard photolithographic techniques were employed to fabricate 300 μm circular HPTs with 250 μm windows. Some of the layers were also fabricated as bipolar transistors. For optical measurements, a monochromatic light source with a spot size

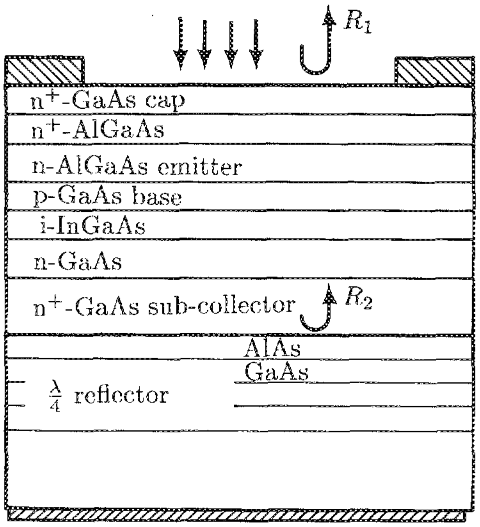

FIG. 1. Schematic layer structure of the investigated devices.

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of $\approx$ 500 μm was used. Spectrum of this source was calibrated by a Si detector. Also, AlGaAs and InGaAs strained-layer graded index separate confinement heterostructure (GRINSCH) lasers with 8500 and 9000 Å wavelengths were grown and fabricated for use in optical gain measurements at high incident power levels.

First, heterojunction bipolar transistors (HBTs), fabricated on wafers without the reflectors, were characterized by dc current-voltage (I-V) measurements. For 125 μm circular emitter devices a maximum current gain h_{FE} of 1800 at a collector current of $I_C = 50$ mA and a collector emitter voltage $V_{CE} = 8$ V was obtained. However, the current gain at low injection levels was relatively low, $h_{FE} = 10$ at $I_C = 100$ μA, $V_{CE} = 2$ V. This strong dependence of gain on the collector current is attributed to surface recombination at the emitter base periphery, as also verified by a strong dependence of the current gain on device size (or area to periphery ratio).

Under pulsed laser illumination, optical gains of over 500 at 8500 Å (calculated $\eta = 25\%$) and $\approx$ 150 at 9000 Å (InGaAs region absorption wavelength, $\eta = 6.7\%$) were observed at $V_{CE} = 5$ V and $I_C = 30$ mA for the HPT without reflector. The dark current measured for a 250 μm device was 5 pA (1×10^{-8} A/cm^2). The optical gain did not degrade at lower current levels as much as in the HBT case. Optical gains of more than 10 at 0.3 μA collector current was measured using a monochromatic light source. This can be explained as surface recombination being less dominant when the emitter mesa and base contact are not formed (reducing the exposed periphery), and the base current is optically generated in the depletion region. The wavelength spectrum of photosensitivity of the HPT is shown in Fig. 2 (solid line), which has two peaks at 8500 and 9000 Å. The latter is solely due to absorption in the InGaAs layer and the first one shows the contribution from the entire active region. The ratio of collector current at 8500 Å to that at 9000 Å was 3.6 and independent of collector-emitter bias above ~2.5 V, indicating the full depletion of the lightly doped collector. This result is consistent with calculations assuming that the collector depletion is the only absorbing layer contributing to the detected current. Thus, the sensitivity of the HPT at longer wavelengths is limited by the thickness of the InGaAs region.

The integration of the HPT with a resonant cavity formed between a buried mirror structure and the epilayer surface, as shown in Fig. 1, enhanced the photosensitivity at certain wavelengths. This buried mirror was composed of a quarter-wave stack of ten AlAs/GaAs layers resulting in a reflection coefficient R of approximately 0.9. The center wavelength was designed to be around 9500 Å, and can easily be altered by changing the thicknesses of these AlAs/GaAs layers. The epilayer surface acts as the other reflector of the cavity, with a reflectivity of $R = 0.3$. The spectral response of the RCE-HPT is shown in Fig. 2 (dashed line), in comparison with the no reflector case (solid line). At the resonant peak of 9000 Å, the detected current increased to $\approx$ 7 times of that for HPT without reflectors by the cavity enhancement effect. The increase at 8500 Å was only 1.7 times. The two spectral responses were normalized at 7500 Å where the cavity effect is negligible.

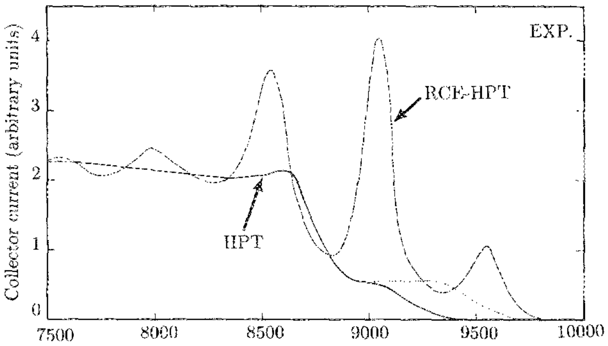

FIG. 2. Spectral response of floating base HPTs: (i) without reflectors (solid line) and (ii) with resonant cavity enhancement (dashed line). The dotted line shows the estimated spectrum for the latter when the cavity influence is removed. Note that the band edge of InGaAs region moves to longer wavelengths due to the inaccuracy of In mole fraction.

The RCE-HPT yields a smaller enhancement of the photosensitivity at 8500 Å (absorption in 0.5 μm InGaAs + GaAs collector) compared to at 9000 Å (absorption in 0.1 μm InGaAs) resulting in almost identical sensitivities at these two wavelengths in contrast with the drastic difference in the thicknesses. As explained below, absorption losses in the base and subcollector in addition to larger absorption by thicker active collector layers degrades the cavity enhancement effect at 8500 Å . Note that in Fig. 2, the sensitivity between the resonance peaks is smaller than that of the conventional HPT without reflectors, owing to the incident light being rejected from the cavity at off-resonance wavelengths. Therefore, the RCE-HPT should be viewed as a high sensitivity detector at selected wavelengths or monolithic integration of a filter with a detector. The calculated finesse of a cavity with reflectivities of $R = 0.3$ and 0.9 and a 0.1-μm-thick absorbing region is 4, which is in good agreement with the experimental value of 3.6 as can be obtained from Fig. 2.

Using a self-consistent calculation for the fields in a resonant cavity of optical length βL with an absorbing region of thickness d, the quantum efficiency of the RCE-HPT, η, is

$$\eta = \left(\frac{1 + R_2 \exp(-\alpha d)}{1 - 2\sqrt{R_1 R_2} \exp(-\alpha d) \cos(2\beta L) + R_1 R_2 \exp(-2\alpha d)} \right) \times (1 - R_1)[1 - \exp(-\alpha d)], \tag{1}$$

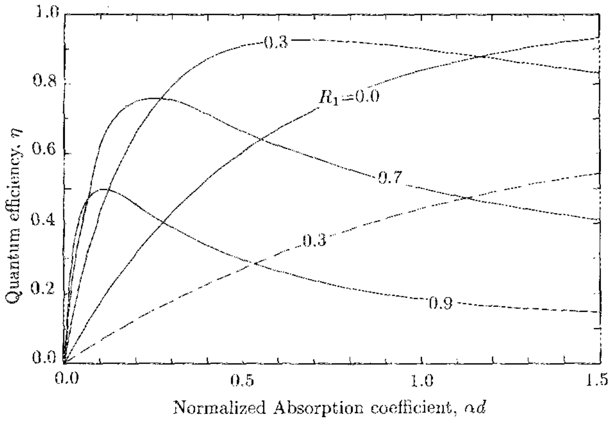

FIG. 3. Calculated quantum efficiency vs αd. Solid lines show η at the cavity mode peaks for $R_2 = 0.9$, and dashed line shows the no reflector case ($R_2 = 0.0$, $R_1 = 0.3$).

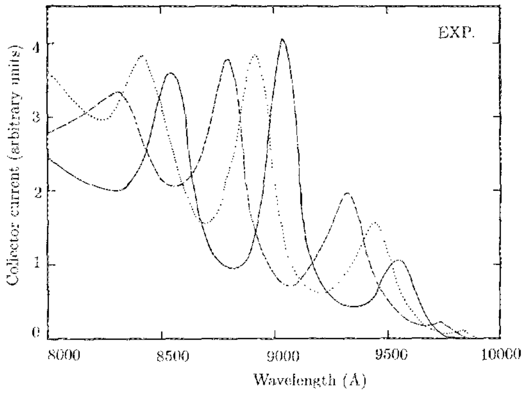

FIG. 4. Spectral response of RCE-HPT as the surface is thinned: (i) as-grown (solid), (ii) etched 350 Å (dotted), and (iii) etched 600 Å (dashed).

where α is the absorption coefficient of the active region, R_1 and R_2 are reflectivities of the top and the bottom mirrors, respectively. On the right side of Eq. (1), the term inside the brackets is the cavity enhancement factor, while the one outside is η for $R_2 = 0$. Maximum η is obtained at $\beta L = m\pi$ and minimum corresponds to $\beta L = m\pi/2$. Note that the cavity is assumed to be lossless except for the active absorption region. Otherwise, d in the first term would have to be replaced by roughly the length of the entire lossy region. At 8500 Å this lossy region is about 1.15 μm, resulting in a cavity enhancement factor of 1.8, which is in very good agreement with the experimental value of 1.7. For InGaAs region the cavity enhancement factor is calculated to be 6.4 and slightly smaller than the experimental results. This can be explained as the current gain increasing with increasing the collector current of the HPT.

Figure 3 shows η at the resonant wavelength as a function of αd (or thickness in μm for $\alpha = 10^4$ cm^{-1}) for different R_1 values as $R_2 = 0.9$ and η for the no reflector case ($R_2 = 0$) is also given by a dashed line. It can be seen that, maximum obtainable η decreases with increasing surface reflectivity R_1, but for the small absorption thicknesses, η can be strongly enhanced by the cavity effect. For 0.1 μm absorption layer ($\alpha = 10^4$ cm^{-1}), η can be improved from 6.7 to 43% (6.4 times) at $R_1 = 0.3$, to 65% (9.7 times) at $R_1 = 0.7$, and to 50% at $R_1 = 0.9$. The quantum efficiency η at a certain αd value is maximized when $R_1 = R_2 \exp(-2\alpha d)$ i.e., for the above case $R_1 = 0.74$. To obtain such a high surface reflectivity, however, it is required that an additional reflector structure is grown above the active device. Furthermore, with this reflector the cavity length and in turn the resonance modes will be fixed.

Fortunately, the epilayer surface supplies a reflection with $R_1 = 0.3$ as described above. Although the inferior surface reflectivity degrades the cavity Q and in turn the sharpness of resonant peaks, it enables us to tune the cavity modes to any desired wavelength, simply by recessing the surface to change the cavity length. This was demonstrated in Fig. 4, where spectral responses of RCE-HPTs of the as-grown structure (solid line), and that after etching the cap layer approximately 350 Å (dashed) and 600 Å (dotted) are given. Therefore, high gain and very fast detectors with high quantum efficiencies at a variety of selected wavelengths can be fabricated on the same wafer.

In conclusion, a RCE-HPT was demonstrated. The device exhibited a very high optical gain (over 500). Integrating the HPT into a resonant cavity, quantum efficiency of the device was drastically enhanced. This novel approach enables us to increase the photosensitivity without compromising the speed of response. We have also demonstrated that high Q, high gain detectors can be made by using a smaller band-gap absorbing region in RCE-HPTs. Resulting wavelength selective detectors can be used in frequency demultiplexing in optical communication systems.

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