Effects of Zn Doped Mesa Sidewall on Gain Enhanced InGaAs/InP Heterobipolar Phototransistor

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Abstract—The excellent detectability of the gain enhanced InGaAs/InP heterobipolar phototransistor (GE-HPT) is demonstrated and attributed to a reduction in the reverse leakage current at the base-collector junction and the enhancement of current gain at the emitter-base junction achieved by using a current blocking structure with a Zn doped mesa sidewall. The common emitter grounded current gain agrees well with the photo-conversion efficiency of several tens of thousands of A/W at incident optical powers in the hundred nanowatt to sub-pieowatt range over several orders of magnitude. The deep mesa structure in the GE-HPT is also effective in ensuring superior isolation of better than 25 dB between adjacent arrays.

Index Terms—HPT, InGaAs, photodetector, phototransistor, Zn diffusion.

I. INTRODUCTION

A heterojunction bipolar phototransistor (HPT) with a large current gain is potentially more advantageous for use as a highly sensitive infrared photodetector and image sensor than a p-i-n photodiode (PD) or an avalanche photodiode (APD) with a practical multiplication factor of at most 10, because the equivalent input noise of an external amplifier can be divided by the internal amplification ratio of the photo-detector. The HPT has been developed mainly for high-speed optical communication with a relatively large bias current [1]. In such applications, no serious problem is posed by a base-collector junction leak current in the nano-ampere region, which is induced at the exposed mesa sidewall of relatively narrow bandgap base material cut from uniform epitaxial layers. However, it is important to reduce the base-collector junction leak current of the HPT when the aim is to detect weak light.

The equivalent input current noise component of the HPT is expressed as

$$\frac{\delta I}{\beta} = \sqrt{2q(I_{c,b0} + I_b + I_{ph}) + (2qI_c + 4kT/RL)/\beta^2} \cdot \sqrt{\Delta f}$$

(1)

where $\delta I$ is the output current noise of the HPT, $\beta$ is the current gain, $I_{c,b0}$ is the base-collector leak current, $I_b$ and $I_{ph}$ are the bias current and photo-induced current, respectively. $I_c$ is the collector current, and $R_L$ is the feedback resistance of the transimpedance amplifier. This equation indicates that shot noise associated with the leak and photo-induced currents in the base-collector junction will dominate as the current gain ($\beta$) increases. Therefore, suppression of the base-collector leak current ($I_{c,b0}$) and enhancement of the current gain ($\beta$) are key issues in terms of reducing amplified shot noise and enhancing the weak light detection performance of HPTs. The surface passivation of such mesa structures has been investigated intensively with a low damage dielectric coating with an ECR plasma CVD, and sulfur treatment [3], [4]. Depleted ledge on the base using a thin wide bandgap emitter is an alternative effective approach [5], [6]. Unlike GaAs/AlGaAs, an oxidized surface in the InGaAs/InP material system tends to accumulate electrons, which increases the current leak at the exposed surface.

In this paper, the surface leak current at the mesa sidewall is effectively suppressed to a level comparable to that of a planar p-i-n PD by the formation of a surface-current block structure with selective Zn diffusion at the mesa sidewall [7]. Enhancement of the current gain is also confirmed. The excellent detectability and photo-conversion efficiency of the gain enhanced (GE)-HPT in the open base mode is demonstrated and confirmed from the current gain and junction characteristics in the base current drive mode.

II. DEVICE STRUCTURE AND FABRICATION

The epitaxial layers for the GE-HPT are grown on a sulfur-doped InP substrate by low-pressure metal organic chemical vapor deposition (LP-MOCVD). Zinc and silicon were used as p-type and n-type dopants, respectively. The epitaxial layers are composed of a heavily doped n⁺ InGaAs (350 nm, $1 \times 10^{19}$ cm⁻³) emitter contact layer, an n-InP (200 nm, $1 \times 10^{16}$ cm⁻³) intrinsic emitter layer, a P-InGaAs (100 nm, $2 \times 10^{17}$ cm⁻³) base layer, an n-InGaAs (1500 nm, $1 \times 10^{15}$ cm⁻³) collector layer, and a lightly doped n-InP (2000 nm, $5 \times 10^{15}$ cm⁻³) buffer layer. The collector layer

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also acts as a photo-absorption layer. Thin n-InGaAsP compositionally graded layers (25 nm each, photoluminescence peaks at 1100 and 1300 nm) are formed at each InGaAs/InP interface.

A schematic drawing of the GE-HPT is shown in Fig. 1. Device fabrication starts with the preparation of two level mesa structures. The emitter contact and photo-absorption mesa areas are formed by using an aqueous solution of phosphoric acid and hydrogen peroxide with an InP emitter and buffer as etch stop layers. Then, a 200 nm thick SiNx film that covered the entire surface was formed with RF plasma CVD. Reactive ion etching with SF6 plasma was employed to remove some part of the SiNx film around the mesa sidewall. Next, a selective Zn diffusion process was carried out in a closed quartz ampoule [8]. The Zn diffusion depths were 0.6 and 0.3 µm for InP and InGaAs, respectively. Consequently, the metallurgical PN-junction between the p-InGaAs base and the n-InGaAs collector (photo-absorption layer) exposed at the sidewall of the mesa disappears from the surface, and new PN-junctions emerge at the surface of the InP-emitter and buffer. Finally, Ti/Pt/Au metallization was used to provide ohmic contacts. The back surface of the wafer was served as a collector terminal.

Ridge type HPTs without Zn diffusion and PIN photodiodes using a base-collector junction were also fabricated on the same wafer for comparison. Five different square absorption areas with sides of 28, 56, 112, 224, and 448 µm were prepared to separate the bulk and peripheral contributions as is shown in Fig. 2 without (a) and with (b) base electrodes. Contact holes for the base electrode is formed on the Zn diffused InP ledge near the ridge side-wall. The diameter of the emitter contact layer was 9 µm.

The HPT and PDs were probed and tested on-wafer to obtain electrical and optical measurements at room temperature or below. The photo-responses of the HPT and PIN photodiodes were measured with a DC parameter analyzer and a lock-in amplifier under a monochromatic light source, in which a square light flux with a size of around \(6\times6\) µm was projected inside the photosensitive area. The incident light flux was kept at a constant power in the nanowatt range between 400 and 1700 nm using pre-calibrated large area silicon and InGaAs PIN photo-detectors.

III. EXPERIMENTAL RESULTS

The base-collector (B-C) and base-emitter (B-E) junction diode characteristics of the HPT were analyzed with a reverse bias current under dark conditions.

Fig. 3 shows the B-C reverse current-voltage characteristics of 56 µm square with Zn diffusion at the edge (GE-HPT) and without Zn diffusion (ridge-HPT). Reverse leak current of the GE-HPT is nominally 100 times smaller than that of the ridge-HPT. Fig. 4 shows the B-C reverse current density at 0.5 V against the side length of the square mesa in GE-HPT and ridge-HPT. The leak current amplitudes are 540 and 4.2 pA in the ridge-HPT and GE-HPT, respectively, with a side length of 56 µm. Therefore, surface leakage is reduced about one hundredfold in the intermediate size device. To separate the contribution from the bulk (Jri) and perimeter (Jrs) of the diode, the reverse bias current density (Jr) is plotted against the inverse of the side length as expressed in (2) [9]:

\[
\text{Jr} = \text{Ir}/S = \text{Jri} + 4\text{Jrs}(1/L).
\]
Fig. 4. Size dependence of reverse current leakage at base-collector junction at −0.5 V, in ridge-HPT and GE-HPT.

Table I summarizes the y-intercept and slope of the BC and BE leak current at a reverse bias of 0.5 V in the GE-HPT and ridge-HPT, respectively. The leak current of the intrinsic component is about 1 fA/μm² both in the GE-HPT and ridge-HPT. The perimeter component of the leak current is 8–9 pA/μm in the ridge-HPT, and 0.05 to 0.7 pA/μm in the GE-HPT. Therefore, it is confirmed that the surface leak current at the ledge perimeter is greatly suppressed with the Zn diffusion at the mesa sidewall.

Fig. 5 shows an Arrehenius plot of the BC junction reverse current at 0.5 V in the GE-HPT and ridge-HPT. The device size is 112 μm square. The activation energies are 0.49 and 0.29 eV in the GE-HPT and the ridge-HPT, respectively. The surface leak current and generation current at the depletion layer have a smaller activation energy near the midgap of the InGaAs, while the bulk diffusion current has a larger activation energy corresponding to the bandgap of InGaAs (Eg = 0.75 eV). This agrees with the fact that the ratio of the bulk diffusion current is much larger in the GE-HPT than in the ridge-HPT.

Fig. 6 shows the collector current density versus base current characteristic in GE-HPT and ridge HPT of various sizes. A phototransistor is composed of a transistor and a PD connected in parallel at base-collector junction as shown in Fig. 7 [10]. Surface leak current is induced by resistances connected in parallel to the B-C and B-E junctions. Therefore, the surface leak current \( (I_{ls}) \) acts in the same way as a base bias current \( (I_b) \) and degrades the detectability of the HPT as described by (1). A small-signal current gain against the collector current density is re-plotted from the derivative of the collector current against the base current in Fig. 8. The small-signal current gain is higher in the GE-HPT than in the ridge-HPT, indicating that the ratio of the diffusion current to the recombination and surface leak current is larger at the emitter-base junction with a Zn doped mesa sidewall. Or it is expressed in the smaller shunt resistance across the BE junction in the ridge-HPT. The small-signal gain of a 56 μm square GE-HPT is 10⁶ at a collector current density of 10⁻¹⁰ A. The corresponding DC current gain is 7.2 × 10⁴.

Fig. 9 shows the output current of the PD and a 112 μm square GE-HPT at room temperature and below versus incident optical powers in the several tens of nanowatts to sub picowatt range. The dark current decreases as the temperature is reduced at both

![Fig. 5. Arrehenius plot of BC junction reverse current at −0.5 V in the GE-HPT and ridge-HPT.](image)

![Fig. 6. Collector current density versus base current characteristic in GE-HPT and ridge HPT of various sizes.](image)

![Fig. 9. Output current of the PD and a 112 μm square GE-HPT at room temperature and below versus incident optical powers.](image)
Fig. 7. One-dimensional model of phototransistor.

Fig. 8. Collector current density versus differential small-signal current gain in GE-HPT and ridge HPT of 28 and 56 μm square.

Fig. 9. Photo-response of GE-HPT and PD of the same size at room temperature and below. Bias voltage = 0.5 V, incident wavelength = 1550 nm.

IV. DISCUSSION AND SUMMARY

The excellent detectability of a gain enhanced InGaAs/InP heterobipolar phototransistor (GE-HPT) in the sub picowatt range is demonstrated and attributed to the reduction of the reverse leakage current at the base-collector junction and the enhancement of the current gain at the emitter-base junction that is achieved by employing a current blocking structure with a Zn doped mesa sidewall. The relatively narrow bandgap InGaAs PN junction exposed at the mesa sidewall is replaced with a relatively wide bandgap InP PN junction at the ledge by selective Zn diffusion. The activation energies of the reverse leakage current are 0.49 and 0.29 eV in a GE-HPT with Zn diffusion and a conventional ridge type HPT, respectively, indicating that the generation and recombination effects of the surface defects at the InGaAs sidewall are effectively suppressed.

In the Shockley-Read-Hall statistics, generation and recombination of carriers via deep levels (U) are expressed as [13]

\[
U = \frac{\left( V_{th} \sigma_{0} \eta_{i} \right) \left( p_{n} n_{n} - n_{i}^2 \right)}{\sigma_{p} \left[ p_{n} + n_{i} \exp \left( \frac{E_{g} - E_{c}}{kT} \right) \right] + \sigma_{n} \left[ p_{n} + n_{i} \exp \left( \frac{E_{g} - E_{v}}{kT} \right) \right]}
\]

(3)
Fig. 11. Photo-responsivity distribution of GE-HPT measured with optical fiber microscope. (Detector area: 56 μm square, modulation frequency: 230 Hz.)

\[ U = \frac{V_{th} \sigma_0 N_i}{2 \cosh \left( \frac{E_c - E_n}{kT} \right)} \]

\( U \) is zero in the thermal-equilibrium condition (i.e., \( n_i = n_0^2 \)). Therefore, generation and recombination of carriers does not take place via surface defects at the InGaAs sidewall after the selective Zn diffusion, if any, because carrier equilibrium condition is satisfied with heavy Zn doping. In the depletion condition and in case when capture cross section of hole and electrons are same, the above expression is simplified as

\[ G = -U = \frac{V_{th} \sigma_0 N_i n_i}{2 \cosh \left( \frac{E_c - E_n}{kT} \right)} \]

It means that generation rate via crystalline defects are approximately expressed as the intrinsic carrier concentration \( n_i \) divided with the generation lifetime. So, surface leak current decreases drastically when the surface depletion layer at the air exposed InGaAs disappears with heavy Zn doping and it extends only at the relatively wide bandgap InP surface.

The common emitter grounded current gain agrees well with the photo-conversion efficiency of the several tens of thousands of A/W at incident optical powers in the hundred nanowatt to sub-picowatt range over several orders of magnitude. The common emitter breakdown voltage of the GE-HPT is several volts, which is 10 times smaller than common-base breakdown voltage. The small breakdown voltage indicates the possibility of a silicon IC compatible avalanche type infrared photo-detector.

The photo-response of the GE-HPT is in proportion to the 1.3th power of the incident optical power. Enhancement of the current gain at a lower incident power will be important in terms of further improving the detectability. The deep mesa structure in the GE-HPT is also effective in ensuring a superior isolation between adjacent arrays of better than 25 dB.

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