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InGaP/GaAs Heterojunction Phototransistor Powered by an On-Chip GaAs Solar Cell for Energy Harvesting

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Abstract

An InGaP/GaAs heterojunction phototransistor (HPT) and a GaAs solar cell were monolithically integrated on an HPT epitaxial wafer, and the battery-free operation of the HPT was successfully demonstrated for energy harvesting. The GaAs solar cell with the InGaP window layer was fabricated using the base and collector layers of the HPT epitaxial wafer. Although the thicknesses and doping of the layers are optimized for the HPT's performance but not for the solar cell's, the obtained maximum conversion efficiency of 5.8 % was high enough to operate the InGaP/GaAs HPT in the two-terminal (2T) configuration. Photocurrent of 0.63 mA was obtained when both the 2T-HPT and solar cell were illuminated with a halogen lamp of 35 mW/cm^2.

1. Introduction

A heterojunction phototransistor (HPT) is more attractive than photodiodes because of its good compatibility with a heterojunction bipolar transistor (HBT), high photoresponse even at low bias voltage and immunity from avalance noise [1]. HPTs are used in configurations of both two-terminal (2T) with a floating base and three-terminal (3T) with the forced base current. Although a higher responsivity was obtained in the 3T configuration of the InGaP/GaAs HPT [2], [3] the 2T configuration also showed an optical gain [1] and is more suitable to be monolithically integrated with a GaAs solar cell on a chip for battery-free operation of the InGaP/GaAs HPT, which will be useful in remote sensor-network applications.

2. Experiment

The InGaP/GaAs HPT epitaxial wafer was grown on a S.I. GaAs (100) substrate using a metal-organic chemical vapor deposition (MOCVD) system. The fabrication process of the InGaP/GaAs was described in detail elsewhere [2], [3]. The emitter area was 160,800 μm^2, which was larger by four orders than those of typical HBTs in order to increase the collector photocurrent. The emitter structure consisted of 10 finger-shaped electrodes, each with a size of 4 μm$\times$2100 μm so that the effective emitter area could be large without causing emitter crowding.

It should be noted that the 2T-HPT has the emitter-ledge passivation. An emitter ledge was formed by leaving a portion of the InGaP emitter in etching of InGaP, as shown in Fig. 1. The emitter ledge covers the surface of the external base at the emitter edge and suppresses surface recombination near the emitter edge. A GaAs pn junction was made of a p$^+$ base and n collector layers as a solar cell next to the 2T-HPT. The InGaP emitter layer was used as a window layer to suppress the surface recombination in the heteroface solar cell. Figure 1 shows the schematic cross section of the fabricated InGaP/GaAs 2T-HPT and GaAs solar cell. Figure 2 shows an equivalent circuit diagram of the monolithically integrated InGaP/GaAs 2T-HPT and GaAs solar cell. In the diagram, the collector electrode of the 2T-HPT was wire-connected to the p$^+$ electrode of the solar cell, and the emitter electrode of the 2T-HPT was wire-connected to the n electrode of the solar cell. In this wiring, the photovoltage will be directly applied between the emitter and collector electrodes of the 2T-HPT and the photocurrent of the 2T-HPT is also the photocurrent of the solar cell. The photovoltage and photocurrent are measured at the operating point with a voltmeter and ammeter, as shown in Fig. 2.

A halogen lamp was used as a white light source, and the power density was varied up to 35 mW/cm^2 by varying the current. Both the 2T-HPT and solar cell were uniformly illuminated under the lamp. The minimum area of the solar cell was 0.283 cm^2 in order for the short-circuit current of the solar cell to be higher than the photocurrent of the 2T-HPT under illumination.

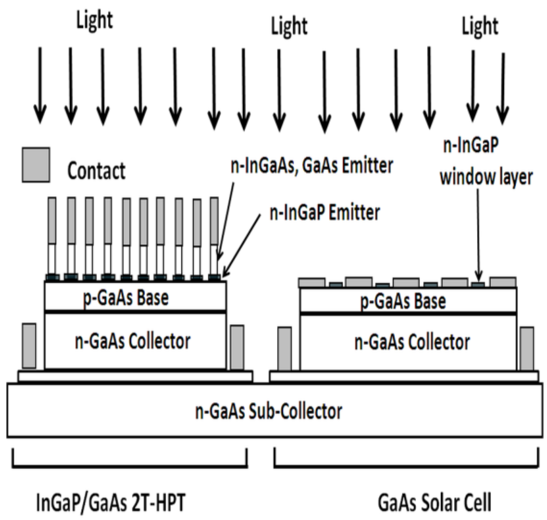

Fig. 1 Schematic cross section of the monolithically integrated InGaP/GaAs 2T- HPT and GaAs solar cell.

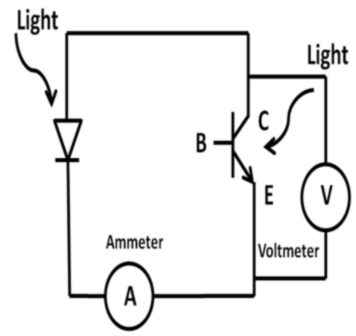

Fig. 2 Equivalent circuit diagram of battery-free operation of the InGaP/GaAs 2T-HPT by the on-chip GaAs solar cell under illumination. The 2T-HPT was operated in the 2T configuration.

3. Results and Discussion

Figure 3 shows the I-V characteristics of the GaAs solar cell and the InGaP/GaAs 2T-HPT measured separately by an HP4155A semiconductor parameter analyzer under illumination with a power density of 35 mW/cm^2. Since the short-circuit current of the solar cell is made higher than the photocurrent of the 2T-HPT, the operating point shown as a crossing point of two curves can be found.

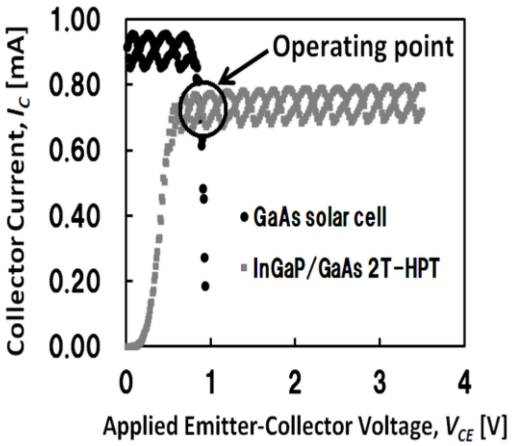

Fig. 3 I-V characteristics of the GaAs solar cell and the InGaP/GaAs 2T-HPT under illumination with a power density of 35 mW/cm^2.

The solar cell exhibited a short-circuit current of 0.89 mA, open-circuit voltage of 0.9 V and conversion efficiency of 5.8 %. Note that the doping concentrations and thicknesses of the base and collector layers were optimized for the HPT's performance but not for the solar cell's. The collector doping and thickness are 1x10^{16} cm^{-3} and 600 nm. In contrast to the conventional GaAs solar cell, the n layer is too thin for high short-circuit current. Nevertheless, the obtained efficiency is high enough to find an operating point of the InGaP/GaAs 2T-HPT. The operating point is expected from the crossing point at about 0.87 V and 0.732 mA under illumination with a power density of 35 mW/cm^2.

Figure 4 shows the photocurrent of the 2T-HPT powered by the on-chip GaAs solar cell measured for various power densities of light. The photocurrent and photovoltage for 35 mW/cm^2 are 0.63 mA and 0.81 V, respectively. These values are slightly off from those expected from the crossing point in Fig. 3. Note that the photocurrent obtained from the crossing point is a midpoint between the highest and lowest in the oscillation of the photocurrent, which was caused by that of the lamp intensity with a frequency of 60 Hz due to the AC lamp power. Therefore, the operating voltage and current can be affected by the oscillation of the lamp intensity.

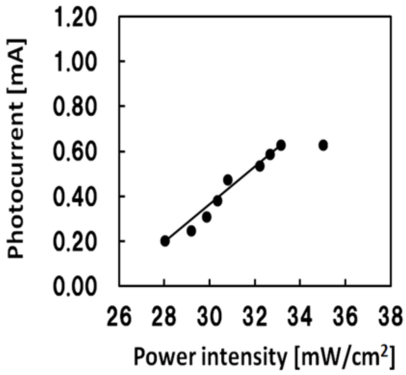

Fig. 4 Photocurrent of the 2T-HPT powered by the on-chip GaAs solar cell under illumination with various light intensities.

In Fig. 4, an almost linear characteristic of the photocurrent as a function of the power density is clearly seen for the power densities lower than 35 mW/cm^2. Such linearity is suitable for a practical application to a photodetector. The photocurrent appears to saturate or decrease with further increasing the power density from 33 mW/cm^2. This may be associated with the increased temperature of the devices by heat dissipation.

4. Conclusions

The InGaP/GaAs HPT and GaAs solar cell were monolithically integrated on the HPT epitaxial wafer. The battery-free operation of the InGaP/GaAs HPT in 2T configuration was successfully demonstrated for the first time. The GaAs solar cell made of the base and collector layers showed a short-circuit current of 0.89 mA, open-circuit voltage of 0.9 V and conversion efficiency of 5.8 % when both devices were illuminated with a halogen light of 35 mW/cm^2. Although the layers are not optimized for the solar cell's performance, the GaAs solar cell with an area of 0.283 cm^2 was able to provide enough power for operation of the 2T-HPT. The battery-free operation of the InGaP/GaAs HPT powered by the on-chip GaAs solar cell is attractive in remote sensor-network applications.

References

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[3] P. H. Than *et al.*, Materials Research Society Spring Meeting (2015) CC11.03.