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Optical Responsivity Enhanced InGaAs/InP Heterojunction Phototransistor Arrays

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1. Introduction

InGaAs PIN photodetectors are widely used devices for near infrared light of 1.1um ~ 1.7um wavelength. But InGaAs PIN photodetectors have structural limitation of low responsivity[1][2]. In low light level, this PIN devices couldn't flow enough amount of current which is indispensable to analog signal processing. For more improved optical responsivity, avalanche photodiode(APD) was introduced instead of PIN photodetector, but the APD has two major problems, large noise and extremely high bias voltage. InGaAs PIN devices still be the most widely used photodetectors for near infrared light detection. We need highly sensitive photodetectors which can flow more amount of current under the same low light intensity.

With this motivation, we present the optical gain enhanced highly sensitive heterojunction phototransistors(HPT) and their one dimensional arrays for microspectrometer applications.

2. Design and Characterization

Device Structure

The epitaxial structure of the proposed HPT mainly consists of emitter, base, collector and subcollector layer as was shown in Fig. 1. The device's epi-wafer was grown by MBE on a semi-insulating InP substrate. Carbon was used as the p-type dopant while Si was used as the n-type dopant. The emitter consists of heavily doped 60nm InGaAs($2*10^{19}$)/40nm InP ($2*10^{19}$) cap layer on a 60nm InGaAs($6*10^{17}$) emitter layer to lower emitter contact resistance. Thin undoped InGaAs spacer layer being formed on InGaAs(60nm, $2*10^{19}$) base layer. Beneath the base layer, collector layer was formed by thick InGaAs absorption layer(1000nm, $2*10^{16}$). One very thin InGaAs subcollector was employed as a etch stop to expose the collector contact surface without over etching.

To increase optical gain and responsivity, the HPT's epitaxial layer structure was optimized as the collector doping reduced and the collector thickness increased.[3][4] By placing the absorber in the collector depletion region of an HPT, the photogenerated current is electrically amplified, giving the device gain. Heterojunction phototransistors are particularly attractive as they provide optical gain without the excess noise that characterizes avalanche photodiodes.

Operation

In the floating base two terminal configuration, basic operation mechanism is described as follows. Under the equilibrium condition without any external bias, when the electron hole pairs are generated by photon absorption, electrons drift toward collector while holes drift toward floating base region due to built-in junction field. The excess hole concentration in base region lower the emitter-base built-in barrier which cause relatively lots of electron injection from the emitter layer due to the emitter base dopant concentration difference.[5][6] Some of the injected electrons recombine with holes and others are diffused across the thin base layer and reach the base-collector depletion region. These electrons drift toward the collector layer and cause the collector-emitter photocurrent. Under the condition with external bias, due to the external bias, more amount of electron hole pairs are generated. The generated electron hole pairs further lower the emitter-base built-in barrier and cause large photocurrent.

Layer	Material, Dopant, Doping	Thickness(nm)
Emitter	InGaAs, Si, $2 * 10^{19}$	60
	InP, Si, $2 * 10^{19}$	40
	InP, Si, $6 * 10^{17}$	60
Spacer	InGaAs, Undoped	5
Base	InGaAs, C, $2 * 10^{19}$	60
Collector	InGaAs, Si, $2 * 10^{16}$	1000
Etch-stop	InP, Si, $2 * 10^{19}$	10
Subcollector	InGaAs, Si, $2 * 10^{19}$	400
Substrate	InP, S.I	

Fig. 1. Epitaxial Structure of the proposed HPTs

Fabrication

With the previously introduced InP/InGaAs HPT structure, 1 by 16 one dimensional arrays have been fabricated. The fabrication process step is similar to the HBT's process step. The HPT one dimensional array, shown in Fig. 2, was fabricated by wet etching the InP with a diluted HCl solution and the InGaAs with a solution of H3PO4, H2O2 and H2O. Non alloyed Ti/Pt/Au was used for all of the device contacts.

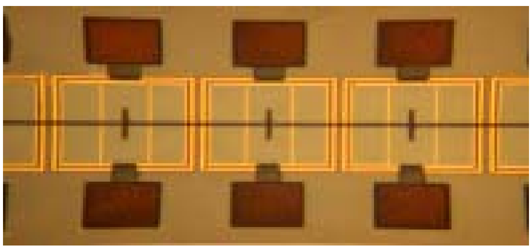

Fig. 2. Microphotograph of the fabricated HPT array

Test Results

1 by 16 InP/InGaAs heterojunction phototransistor arrays with floating base terminal have been fabricated and characterized using frontside optical injection through the top layer. The photocurrent was measured with light incident from a tunable laser source(1550nm wavelength) and using Keithley 4200 semiconductor parameter analyzer.

In Fig. 3 we have plotted two terminal HPT's collector current against collector-emitter voltage for different optical powers. The absorption area was 80um * 200um, measured dynamic range was 933,595:1, average dark current was 300nA and light current was 80.5mA under the 1.66mW incident optical power at 2V bias. The device's maximum optical responsivity was measured and found to considerably exceed that reported by conventional PIN photodetectors. The maximum optical responsivity is 280 A/W, which was found to exceed that reported by S. Chandrasekhar[7] and S.A. Bashar.[8]

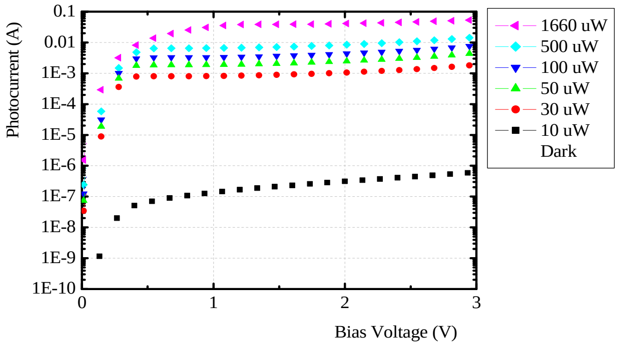

Fig. 3 Two terminal optical properties of HPT's with different incident power

The origin of this high responsivity is the internal gain enhancement mechanism of the HPT which was previously described. With the results of these devices, we can easily implement highly sensitive Near IR detection systems to recognize very weak optical signals.

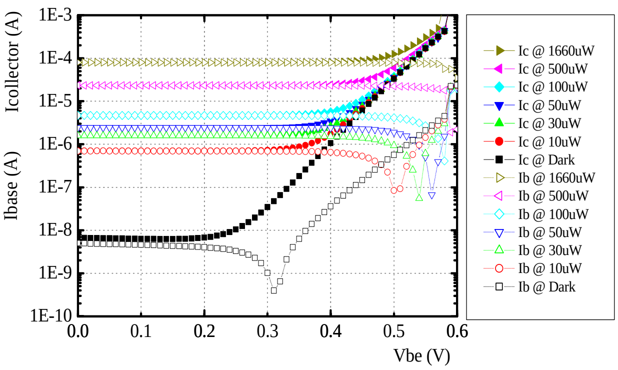

Fig. 4 Three terminal optical properties of HPT's with different incident power

In case of three terminal HPT, the effects of the optical absorption are further illustrated in Fig. 4. The optical absorbing area of this device was 50um * 70um which is smaller than previously described two terminal HPT. The base and collector current characteristics of this device are shown for a series of different optical powers. In Fig. 4, we see the notch shape corresponding to the reversal in the base current, which moves to a higher base-emitter bias with increasing optical power while the characteristic is unchanged at high biases. At low bias voltages the base current saturates at a value corresponding to the illuminated optical power, in this case HPT operate as a photodetector. Fig. 4 also shows the collector current's saturation value at low bias shifting steadily to higher current levels with increasing optical power as expected. At high bias voltages, the currents converge independent of the incident optical power, in this condition, HPT operate as a transistor. The maximum measured current gain was above 3,500 at the base-emitter voltage of 0.54V with the 50uW incident optical power. Under a critical bias voltage, the dark current can be minimized without degradation in light current. So we can easily increase dynamic range of HPTs.

3. Conclusions

In this work, we present optical properties of gain enhanced, highly sensitive InP/InGaAs heterojunction phototransistor(HPT) 1 by 16 array with two and three terminal configurations for Near IR light detection. To increase optical gain and responsivity, the HPT's epitaxial layer structure was optimized. The device exhibited significant current gain of 3,500 and maximum optical responsivity of 280A/W which is significantly higher than that of ever reported HPTs and conventional PIN photodetectors with the same light absorbing area. Although this device shows high gain and responsivity, the optical cut-off frequency of the HPT was measured to be 6.1GHz, which is enough speed for most optical applications.

Acknowledgements

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