High Efficient 850 nm and 1,310 nm Multiple Quantum Well SiGe/Si Heterojunction Phototransistors with 1.25 Plus GHz Bandwidth (850nm)

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Abstract

The Si$_0.5$Ge$_0.5$/Si multiple quantum wells (MQW) are placed between the base and collector of Si/SiGe heterojunction bipolar transistors as light absorbing layers. The phototransistor with high responsivity and bandwidth at 850 nm is demonstrated. Efficient near infrared (1,310 nm) photoresponse also achieved in this device. The results indicate the Si/SiGe phototransistor is suitable for front-end photoreceivers in the high-speed optical communication applications

Introduction

With high gain and low noise, the phototransistor can be used in the front end of an optical receiver. However, due to the large absorption depth of Si (~20 µm) at 850nm [1] and forbidden absorption at 1310 nm, the Si based photodetector has limited detection efficiency and wavelength. The integration of SiGe into Si can not only enhance the absorption of Si-based detectors, but also extend the cut-off wavelength into 1310 nm (Fig.1 and Fig.2). In this work, a novel SiGe phototransistor structure is proposed. The multiple Si$_0.5$Ge$_0.5$/Si quantum wells (MQW) are placed between the base and collector of Si/SiGe heterojunction bipolar transistors as the light absorption layers (Fig.3). Both electrons and holes are generated in the base-collector region under light exposure, electrons are swept to the collector as parts of the initial photocurrent of the heterojunction phototransistor (HPT), and the generated holes diffuse to the base region and inject into the emitter by lowering the base-emitter energy barrier. The barrier lowering allows a large amount of electrons to diffuse across the base to the collector and amplifies the initial hole current. The photocurrent at collector terminal was then largely enhanced.

Electrical Results

The phototransistor is fabricated by a baseline process of heterojunction bipolar transistor with $f_T$ = 50 GHz (Fig.4), in which the SiGe multiple quantum wells are thermally stable during fabrication process, and no defects are observed in the final multiple quantum wells (Fig.5). The HPT has an emitter area of 6 µm$^2$ and an optical opening of 14.4 µm$^2$ through the base-collector junction. The base current of phototransistors (Fig.6) is nearly ideal for $V_{BE} > 0.5$ V without light illumination. Under white light exposure, the photo base current changes sign for $V_{BE} < 0.85$, indicating that the photo base current exceeds the regular back injection hole current, and the phototransistor has expected operation. The measured $f_T$ of phototransistor is 25GHz, smaller than the control HBT (48GHz) due to addition of SiGe MQW structure, while $f_{MAX}$ of phototransistor is 25GHz, larger than the control HBT (16GHz) due to the decrease of base-collector capacitance by the undoped SiGe MQW structure (Fig.7). The HPT still remains good RF properties in spite of the addition of the MQW absorption layers.

Optical Results

The phototransistor at emitter open configuration (photodiode mode) has rather low dark current of 5 pA at -1.5V and exhibits 80 µA photocurrent at 850nm light exposure (responsivity ~14 mA/W, Fig 8). The low responsivity is the result of relative thin absorption layer (0.15µm) as compared to the absorption length of Si$_0.5$Ge$_0.5$ at 850 nm (3µm). Under base open configuration (HPT mode), photocurrent is largely enhanced to 9.1mA at $V_{CE} = 1.5$V, while the dark current still remains low (3nA). The responsivity of SiGe HPT exhibits a high value of 1.47 A/W at $V_{CE} = 1.5$V (Fig.9). Comparing the responsivity of phototransistor to that of photodiode, the photocurrent is amplified by 100 times for a wide range of applied voltage (0.4 to 1.5 V, Fig.10). Since the photocurrent of HPT-mode consists of both photo generated electron and hole currents, and only the photo generated hole current can be amplified, the optical current gain is smaller than the current gain under normal transistor operation, 150 - 300 (inset of Fig. 10). The response of phototransistor for 1310 nm is measured at the same device. The photocurrent and responsivity under photodiode operation are 0.6 nA and 4.1x10$^{-5}$ A/W, respectively (Fig.11). The low response is due to the long absorption length (50 µm at 1310 nm). Under the HPT-mode operation, the photocurrent and responsivity was increased to 1 µA and 0.15 A/W, respectively (Fig.12). As consequence, the internal quantum efficiency is 14%. This high value was
only observed previously on the thick SiGe photodiode with the waveguide structure [2]. The optical/electrical frequency response of the SiGe phototransistor is explored through impulse response measurement. An 830nm mode-locked Ti: Sapphire pulse laser with 50ps FWHM is coupled through a fiber to the phototransistor (Fig.13) and a sampling oscilloscope records the response of phototransistor. At $V_{CE} = 1.5V$, the SiGe phototransistor has 10% - 90% rise time of 38ps, while the FWHM is 208ps (Fig.14). Followed by Fourier transformation of the time domain response to the frequency domain, the optical-electrical -3 dB bandwidth is 1.25GHz (Fig.15). However, the non-zero response of the device is observed after 0.1 ns of the initial pulse, probably due to the slow diffusion time of photo generated carriers. Furthermore, due to the limitation of the oscilloscope bandwidth (20GHz), the bandwidth of phototransistor should be larger than 1.25 GHz. The high frequency (100 KHz) C-V shows that base-collector junction capacitance is 11 fF with ~ 100 Ω series resistance (Fig.16). The low RC value also indicates that the diffusion time should be the dominant factor to shut the photocurrent.

**Summary**

In summary, the SiGe/Si multiple quantum well heterojunction phototransistor with ultra-high responsivity of 1.47A/W and a bandwidth >1.25GHz at wavelength of 850 nm is demonstrated at operation voltage as low as ≤ 1.5 V. In addition, the detection at 1310 nm with 14% internal quantum efficiency is also presented. The results indicate the Si/SiGe phototransistor is suitable for front-end photoreceivers in the high-speed optical communication applications.

**Acknowledgement**

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**References**


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![Fig. 1 Absorption length of SiGe for wavelength of 850 and 1310 nm.](image1)

<table>
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<tr>
<th>850nm</th>
<th>Si</th>
<th>Si$<em>{0.8}$Ge$</em>{0.2}$</th>
<th>Si$<em>{0.5}$Ge$</em>{0.5}$</th>
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<td>Absorption Length (µm)</td>
<td>20</td>
<td>9</td>
<td>~3</td>
<td>~0.1</td>
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<td>1310nm</td>
<td>Absorption Length (µm)</td>
<td>~∞</td>
<td>~∞</td>
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</table>

**Growth:**

| Critical Thickness (nm) | --- | 13 | 5 | ~1 |
| Thermal Stable          | YES | YES | YES | NO |

![Fig. 2 Estimated absorption and critical thickness of SiGe thin film. Si$_{0.5}$Ge$_{0.5}$ is optimum one among 4 structures.](image2)

![Fig. 3 Band diagram of the SiGe heterojunction phototransistor.](image3)

![Fig. 4 XTEM image of SiGe/Si heterojunction phototransistor.](image4)
Fig. 5 XTEM image of SiGe/Si MQW after fabrication process.

Fig. 6 Gummel plots of a SiGe phototransistor with and without 850nm light. Note that the photo base current changes sign at ~0.85 V.

Fig. 7 The $f_t$ and $f_{MAX}$ of SiGe phototransistor. Control HBT has $f_t = 48$ GHz and $f_{MAX} = 16$ GHz

Fig. 8 Responsivity and photocurrent of SiGe HPT and control HBT at 850nm under emitter open (photodiode-mode) operation.

Fig. 9 Responsivity and photocurrent of SiGe phototransistor and control HBT at 850nm under base open (phototransistor-mode) operation.

Fig. 10 Optical current gain of Si/SiGe phototransistor at 850nm. The inset shows the DC gain of normal transistor operation.
**Fig. 11** Photocurrent and responsivity at 1310 nm for photodiode-mode operation.

**Fig. 12** Photocurrent and responsivity at 1310 nm for HPT-mode operation.

**Fig. 13** The setup for time domain photoresponse measurement.

**Fig. 14** Impulse response of SiGe HPT.

**Fig. 15** The optical bandwidth spectrum of SiGe HPT at 850 nm.

**Fig. 16** The BC junction capacitance of SiGe HPT.