Performance enhancement of high-speed SiGe-based heterojunction phototransistor with substrate terminal

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Heterojunction phototransistors (HPTs) are requested to have high electrical bandwidth (~1 GHz) performance for their application of high-speed digital fiber communication. In this letter, a method is disclosed to enhance the speed performance of Si/SiGe-based HPTs, which can overcome the low quantum efficiency drawback (~0.1 A/W) of Si-based high-speed photodetectors at the wavelength of 850 nm due to its large internal gain. By use of the substrate terminal of HPT, the speed performance can be enhanced greatly with much less reduction in optical gain as compared to the traditional technique with base-terminal-bias. Under proper optical power excitation and the common ground of substrate and emitter terminals, we can achieve 1.8 GHz fast-Fourier-transformed electrical bandwidth with 0.7 A/W responsivity simultaneously. The demonstrated device structure can serve as a key component in the short-reach fiber communication system. © *2004 American Institute of Physics*.
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Heterojunction phototransistors (HPTs) attract lots of attention due to their extremely high responsivity[1] and good ability to be integrated with high-speed heterojunction bipolar transistors (HBTs).[2,3] The integrated heterojunction phototransistor (HPT) has lots of applications in microwave photonics communication systems, such as optoelectronic mixer,[4] narrowband photo-receiver circuits,[5] and direct-optical-injection-locking clock recovery circuits.[6,7] However, the traditional two-terminal HPT is seldom used in high-speed digital fiber communication system due to its poor electrical bandwidth ($f_{3\text{ dB}}$) performance (~1 MHz). By applying a dc bias voltage or current on the base terminal of HPT to remove the photogenerated hole in the base–emitter potential barrier, the speed performance of HPT can be enhanced significantly.[8–10] Ultrahigh speed (~200 GHz) with low responsivity performance (<0.1 A/W) of InAlAs/InGaAs HPT has been demonstrated[8,11] by use of such technique. Although this technique can increase the speed performance of HPT, its photocurrent gain will be reduced seriously.[8,11] In addition, the base bias current will result in large dark current and huge standby power consumption. This letter reports a method to improve the speed performance of HPT without serious reduction in photocurrent gain and increase in dark current. The structure of the demonstrated device is Si/SiGe-based HPT, which is operated at a wavelength of 850 nm and has a similar device structure to the standard Si/SiGe-based heterojunction bipolar transistor (HBT). Compared with other reported Si-based high-speed photodetectors (PDs) for the applications of short-reach data communication, such as deep trench ***p-i-n*** PDs,[12] silicon on insulator PDs,[13] and resonant-cavity-enhanced PDs with wafer-bonding mirrors,[14] Si/SiGe-based HPT has the advantage of much higher internal optical gain, which can compensate for the low photoabsorption constant of Si material, and a good capability of integrating with Si/SiGe HBT circuits. The demonstrated designing concept of high-speed HPT will play an important role in its applications to high-speed analog and digital fiber communication.

The cross-sectional view of the studied device are given in Fig. 1. The structure of the device is similar to the standard Si/SiGe-based HBT,[15] and the area of emitter is $0.6 \times 10.8\ \mu m^2$. The thickness of poly-Si emitter, $Si_{0.85}Ge_{0.15}$ base, and collector is 300, 90, and 600 nm, respectively. The

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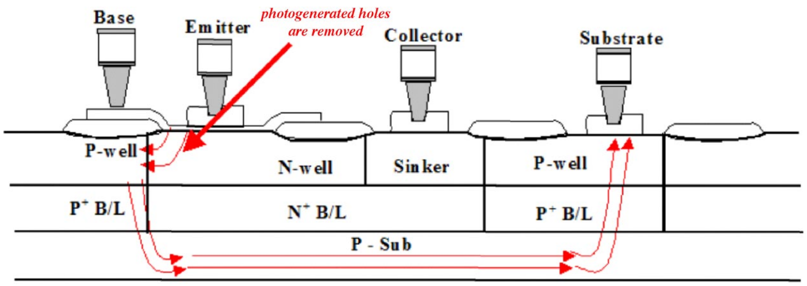

FIG. 1. Cross-sectional view of Si/SiGe-based HPT.

measured dc current gain β is about 81, and the peak f_t and $f_{\max}$ of the measured device are 50 and 25 GHz, respectively. The emitter contact, base contact, collector contact, and substrate contact can serve as the probe pads for using co-planar probe to extract the photogenerated dc or ac signal from the measured HPT and to feed it with V_{BE} and V_{CE} dc bias voltages. In our measurement, the emitter and substrate contacts are common grounded, and the most positive bias voltage is applied to collector.

Figure 2 shows the dc measurement result. We used a semiconductor laser diode, which has a center wavelength at 850 nm, to test the HPT. The optical gain is defined as the measured photocurrent of C–E (base open) operation mode divided by the measured photocurrent of B–C (emitter open) operation mode. As shown in Fig. 2, the obtained responsivity (0.7 A/W) of HPT is much higher than the reported values (<0.1 A/W) of high-speed Si based PDs.[13] To improve the speed performance of HPTs, using dc bias voltage or current to turn on the base-emitter (B–E) junction is necessary.[8] However, this approach will result in huge dark current, large power consumption, and reduction in photocurrent gain.[8,11] For the case of our measured HPT, as shown in Fig. 1, by connecting the *p*-type substrate terminal with the grounded emitter terminal, the *p*-type sidewall of collector and *n*-type collector will behave like a lateral reversed bias *p*–*n* junction, which can remove the photogenerated holes in the base layer without increasing dark current.

Figures 3(a) and 3(b) show the improvement in pulse-width of the measured HPT by utilizing substrate and base terminals, respectively. The transient impulse responses of HPTs were explored by a sampling oscilloscope, which was driven by the 830 nm *Q*-switch laser with 50 ps optical pulse-width. The excited average optical power is about 20.6 μW. As shown in Fig. 3(a), by connecting the substrate terminal with the grounded emitter, the full width at half maximum (FWHM) of responses reduces significantly (2.5 to 0.85 ns) at the expense of slight reduction in average photocurrent (15 to 8.7 μA). On the other hand, after connecting the base terminal with the grounded emitter, as shown in Fig. 3(b), although we can still get significant pulse-width reduction (2.5 to 0.95 ns), the measured photocurrents decrease dramatically (15 to 0.1 μA). It is concluded that the speed performances can be improved more significantly with much less responsivity (photocurrent) reduction by grounding the substrate terminal with emitter as compared to the base-terminal-bias technique. In addition, when the base and substrate terminals are both open, the measured impulse responses show negative tails. These tails are possibly originated from the photogenerated electrons, which are backinjected to the emitter terminal,[8] and can be minimized by applying a proper V_{BE} bias voltage or connecting the base and emitter terminals[8] to forward the B–E junction, as shown in Fig. 3(b). By connecting the substrate and emitter terminals, the excess hole current, which is from the base to emitter (substrate) terminal, can also act as external dc V_{BE} bias voltage and eliminate the negative tail problem, as shown in Fig. 3(a).

Figure 4 shows the variation of FWHM versus V_{BE} bias voltage of measured impulse responses without (a) and with (b) using substrate terminals. As shown in Fig. 4(b), the phe-

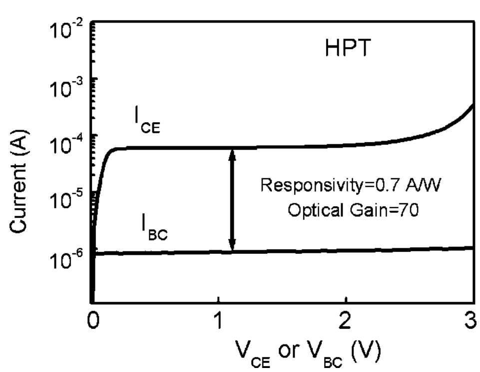

FIG. 2. The measured photocurrent vs V_{CE} or V_{BC} voltages of HPT under C–E (collector–emitter) and B–C (base-collector) operation modes.

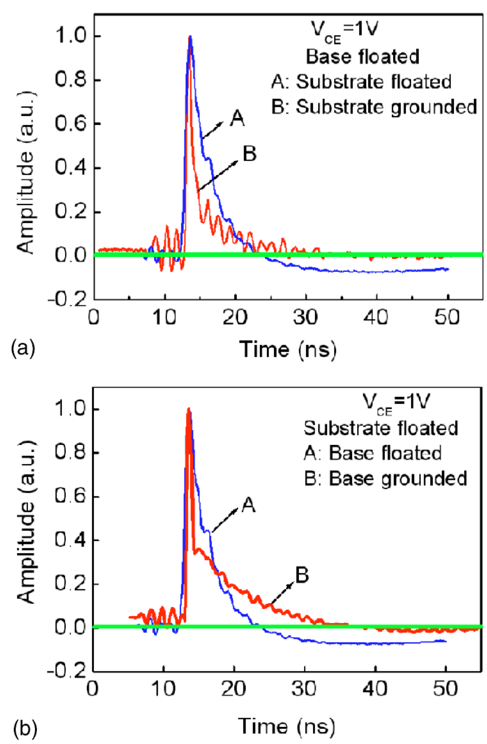

FIG. 3. Measured impulse responses of HPT, (a) traces A and B represent that the substrate terminal is floated and grounded, respectively, and (b) traces A and B represent that the base terminal is floated and grounded, respectively.

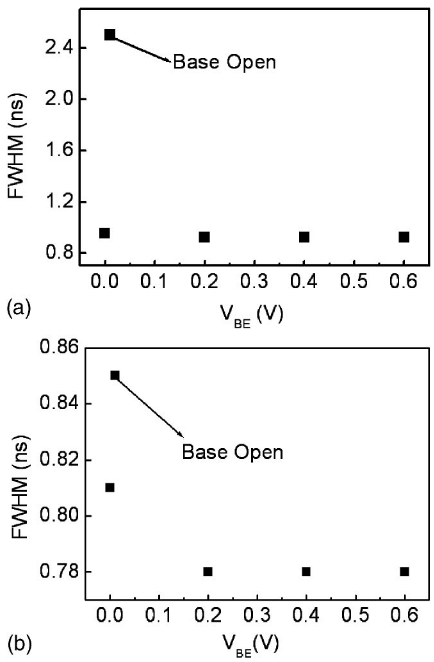

FIG. 4. FWHM of the measured impulse response vs V_{BE} bias voltages, (a) substrate terminal is floated and (b) substrate terminal is grounded.

nomenon of speed enhancement due to V_{BE} bias voltage is not significant after grounding the substrate terminal, because this terminal can provide another path to efficiently remove the photogenerated hole at the B–E interface.

In order to further obtain the highest speed performances of these HPTs, the value of input average optical power was reduced to the level below 1 μW. Under such low optical power excitation, the FWHM and fall-time step of measured impulse responses are affected by the noise slightly. We can still roughly estimate the electrical bandwidth by use of the measured impulse responses and the fast Fourier transform (FFT) technique, because most of the obtained impulse responses do not show significant tail with extremely long time constant in the fall-time step. We expanded the integration time to 10 ns in the FFT calculation process to minimize the inaccuracy. Figure 5 shows the measured impulse response with 90 ps FWHM and 1.8 GHz transformed electrical bandwidth under 4 V V_{CE} bias voltage. The reasonable responsivity (0.7 A/W) and high electrical bandwidth performances (1.8 GHz) of our HPT structure ensure its applications of short-reach data communication. Higher electrical bandwidth performance of demonstrated HPT can be expected by narrowing the width of emitter and fabricating the ring shape substrate terminal to surround the whole collector.

In conclusion, a method for increasing the speed performance of Si/SiGe-based HPT is reported under 830 nm wavelength excitation. As compared to the traditional base-terminal-bias technique, by utilizing the substrate terminal of a HPT, one can achieve superior speed performance with much less photocurrent reduction. Under proper optical power excitation, near 2 GHz electrical bandwidth with rea-

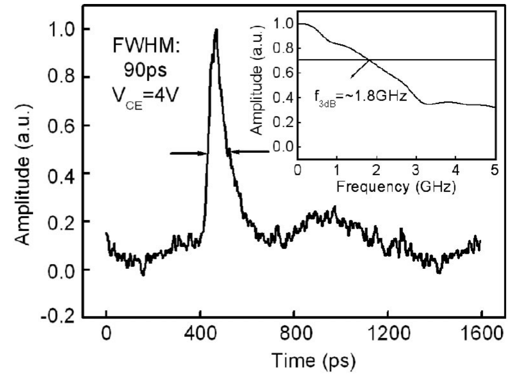

FIG. 5. Normalized impulse response of HPT and its corresponding frequency response is given in the inset.

sonable responsivity (0.7 A/W) has been demonstrated. The demonstrated HPT can be treated as a four terminal device, which includes the substrate terminal due to its functionality of significant enhancement of speed. Some HPT-based optoelectronic integrated circuits can be expected. By properly choosing the dc bias point and injecting the microwave or millimeter-wave signals from local oscillators to the substrate terminal of HPT, the incoming modulated sinusoidal optical signals can be distorted due to the significant speed variation of HPT as shown in Fig. 3. The component of up- or downconverted photogenerated signals can thus be collected from the harmonics of the distorted signals. Optoelectronic mixer with high conversion gain or optical injection-locking oscillator can thus be expected.

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