Heavy Ion and Laser Microbeam Induced Current Transients in SiGe Heterojunction Bipolar Transistor *

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Silicon-germanium (SiGe) hetero-junction bipolar transistor current transients induced by pulse laser and heavy iron are measured using a real-time digital oscilloscope. These transients induced by pulse laser and heavy iron exhibit the same waveform and charge collection time except for the amplitude of peak current. Different laser energies and voltage biases under heavy ion irradiation also have impact on current transient, whereas the waveform remains unchanged. The position-correlated current transients suggest that the nature of the current transient is controlled by the behavior of the C/S junction.

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Silicon-germanium hetero-junction bipolar transistors (SiGe HBTs) have seen a rapid expansion into the market for high-speed digital, rf and microwave circuits because of excellent transistor performance and full integration with commercial silicon CMOS.[1,2] In addition, SiGe HBTs are strong contenders for space applications in extreme environment on account of superior temperature characteristics. It can be used from very low to high temperature owing to the bandgap engineering in silicon.[3−5] Moreover, SiGe HBT technology has generated considerable interest in the space community due to its robustness to total ionizing dose radiation (TID) and displacement damage without any additional hardening.[6−9] Consequently, SiGe HBTs have a possibility to replace bulk-Si component in deep space exploration, which can remove the huge warm box to reduce launch costs and extend the function of remote control of satellite. However, it is shown by experiments and simulations that SiGe HBT can be vulnerable to single event effects (SEEs).[10−12] SiGe HBTs are often employed in high-speed applications, and the data rates of these circuits regularly exceed 1 Gb/s, the detailed characteristics of induced current transients become important and are necessary for a full understanding of the behavior in a particular radiation environment.[13]

The research method of the SEEs on semiconductor devices is injection mainly by heavy ion and pulsed laser micro-beam.[14] The focused ion beam is an experimental method that can obtain spatial information concerning the physical origins of the induced transients and is helpful in understanding anomalous behavior and in validating models used for computer simulation studies.[15] However, this experimental technique has its limitation for investigating SEEs due to the use of low-energy ions at some facilities and the radiation damage including both total ionizing dose and displacement damage (TID and DD).[16] Another method is the pulsed picosecond laser which has been successfully applied to the evaluation of SEEs in a number of different circuits and devices. One attractive feature of the pulsed laser is that the spatial information is obtained without any concomitant radiation damage.[17,18] To investigate the detailed characteristics of induced current transients and spatial information on SiGe HBTs, this study presents heavy ion micro-beam and laser micro-beam position-correlated data, coupled with a detailed device-level data on the temporal profile of induced current transients in this important semiconductor technology.

This technology is chosen due to the large body of published data and simulation results.[19,20] Figure 1 is the 2D cross section of SiGe HBTs manufactured by the Institute of Microelectronics, Tsinghua University. The basic structure is similar to the bulk silicon vertical NPN bipolar transistor and the collector contact is led out by a heavily doped n^+ buried layer and the epitaxial base region of p-type poly-silicon is grown above the local oxidation of silicon (LOCOS). The doping concentration of intrinsic base is about $1\times10^{19}\,\mathrm{cm^{-3}}$, and the content of Ge gradually changes from 0% to 20% at the emitter/base and base/collector junctions. The doping concentration of emitter is $1.5\times10^{20}\,\mathrm{cm^{-3}}$ and the area of each emitter finger is $0.4\times20\,\mathrm{\mu m^2}$. A ring wall of heavily doped boron leads out of the substrate contact near the edge of the device and the emitter and the substrate are connected together via metal interconnection. Figure 2 gives the layout of the SiGe HBT, and the scanning area of the micro-beam is labeled by a black square.

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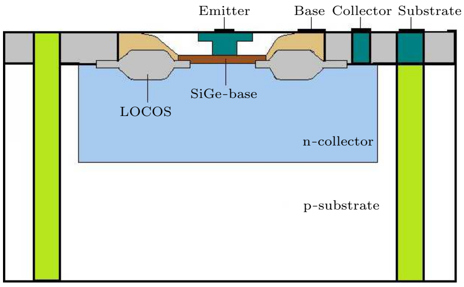

Fig. 1. Schematic diagram of device cross section of the SiGe HBTs (not to scale).

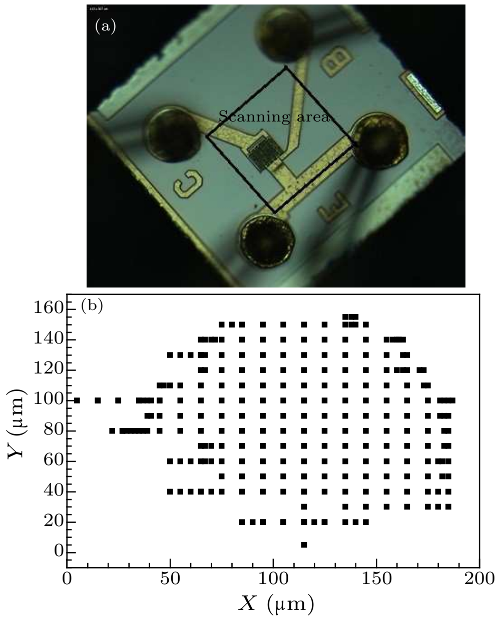

Fig. 2. (a) Scanning area in layout of SiGe HBT. (b) Positions of micro-beam irradiation for the SiGe HBT.

Heavy ion micro-beam and laser micro-beam irradiation were performed in the China Institute of Atomic Energy (CIAE) and Northwest Institute of Nuclear Technology (NINT), respectively. Figure 2(a) gives the layout of the SiGe HBTs which have been exposed to a chemical vapor etch process to remove polymide. Figure 2(b) is the irradiation positions of micro-beam, which is located uniformly on the X-axis from 0 to 200 μm and from 0 to 160 μm on the Y-axis. For the heavy ion micro-beam experiment, a beam of 110 MeV chlorine ions was focused into a 5 μm × 5 μm spot and scanned over generally a 200 μm × 160 μm area. These chlorine ions had a range of 30.6 μm and the current transients on the base and collector were measured and recorded with a Lecroy640Zi 16-GHz (40 GS/s), real-time digital oscilloscope. For the laser micro-beam experiment, the wavelength of the laser micro-beam was 1064 nm with the laser spot size of approximately 1.4 μm in diameter. Devices under test were loaded with base resistance of 1000 Ω, and the collector bias voltage was fixed at 3 V through a load resistor of 50 Ω. The collector and base current transients were measured and recorded with a digital oscilloscope.

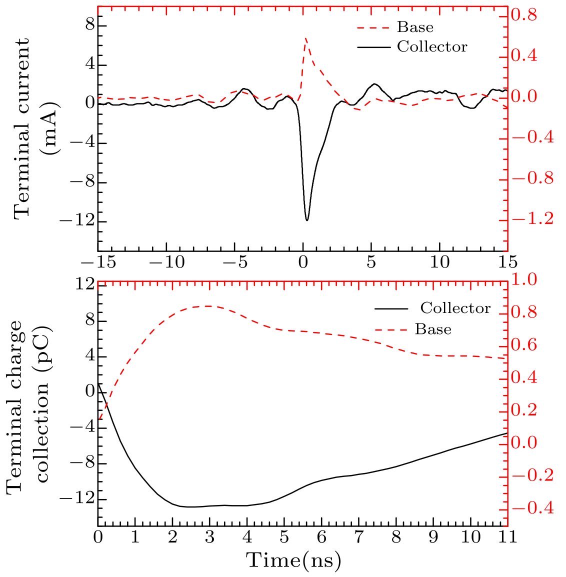

Fig. 3. (a) Base and collector current transients during the pulsed laser irradiation. (b) Base and collector charge collection during the pulsed laser irradiation.

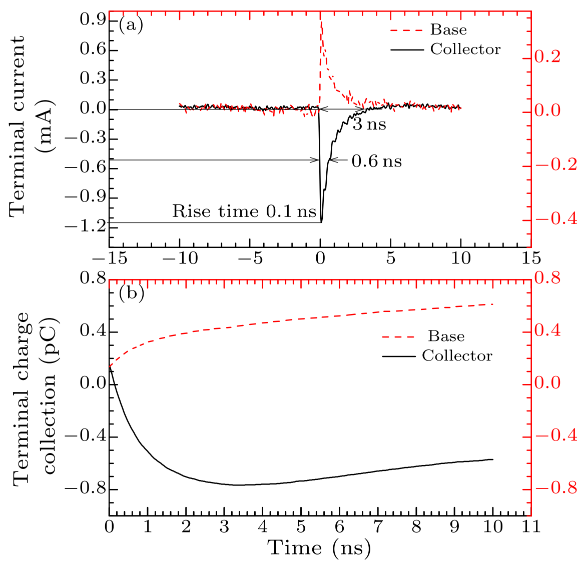

Fig. 4. (a) Base and collector current transients during the heavy ion irradiation. (b) Base and collector charge collection during the heavy ion irradiation.

The results illustrated in Figs. 3 and 4 show typical current transients and charges collection of base and collector induced by pulsed laser and heavy iron micro-beam, respectively. The mechanism of current transient inducement by pulsed laser is similar to that by heavy ion, only different in that the heavy ion produces electron–hole pairs by colliding with molecules and atoms of the target material, while the pulsed laser is through photo ionizing effect. The charge carriers ionized within the depletion region of the C/S junction are separated by the electric field. Electrons are pulled out while holes are dumped into the lightly doped substrate, forming a funnel potential. During the time of drift, the transient currents of the base and collector reach upward to 6 and 12 mA for laser pulse irradiation, and 0.6 and 1.2 mA for heavy ion irradiation. For the process of diffusion, the excess holes begin to diffuse to the C/S junction and accumulate, as they are pushed back by the electric field. The transient current induced by laser pulse in Fig. 3(s), measured at the collector bias voltage of 3 V, exhibits a rise time of 0.1 ns with a full width at half maximum (FWHM) of 0.6 ns and a total duration of 3 ns. Due to the smaller bandwidth of the system, inherent to the single shot measurement technique, the shape of the transient current in Fig. 4(a) induced by heavy ion micro-beam is slightly different from that of pulsed laser. The rise time of 0.1 ns is closer to the theoretical rise time with this 16 GHz bandwidth system, and the FWHM and a total duration are also smaller than that of the transient current induced by the pulsed laser. In addition, the amplitude of transient current produced by laser pulse is much larger than that of current induced by heavy iron micro-beam. The total charge collected after laser pulse irradiation in Fig. 3(b) is much more than that after a heavy ion hitting in Fig. 4(b), and takes a longer charge collection time.

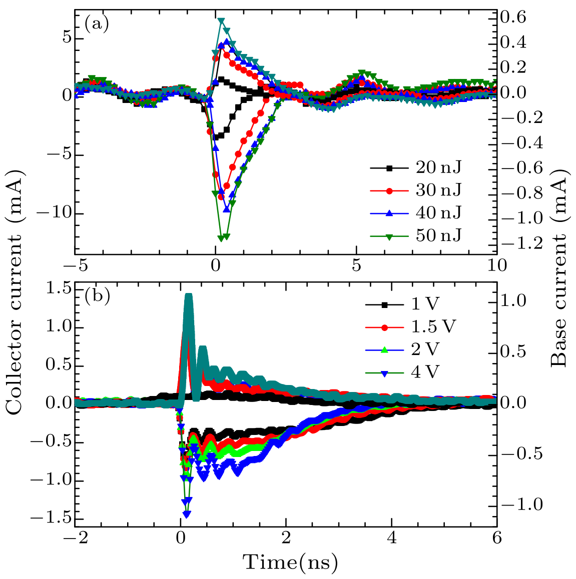

Fig. 5. (a) Dependence of terminal transients on different laser energies. (b) Dependence of terminal transients on different biases during heavy ion irradiation.

Dependence of terminal transients on different laser energies is illustrated in Fig. 5(a). When the laser energy is very low, the laser-induced carrier density is too small to significantly forward bias either CS or BC junction. It can be seen that the higher the energy is, the larger the initial peak terminal current is, and when the laser energy reaches up to 50 nJ which is large enough to make CS and BC junctions strongly forward biased, driving the SiGe HBT into reversely active operation, the peak collector and base current reach up to 14 mA and 8 mA, respectively. Note that substrate, emitter, and base all are grounded here.

The bias dependence of the terminal transients in the central region for 110 MeV chlorine is shown in Fig. 4(b). Due to the high sample rates (40 GS/s) of the real-time digital oscilloscope, the data of transient current is very intensive. It can be seen that the higher the V_{cc} is, the larger the peak current is. This is because the nature of the current transient is controlled by the behavior of the C/S junction, with increasing V_{cc}, the C/S junction driving more reversely.

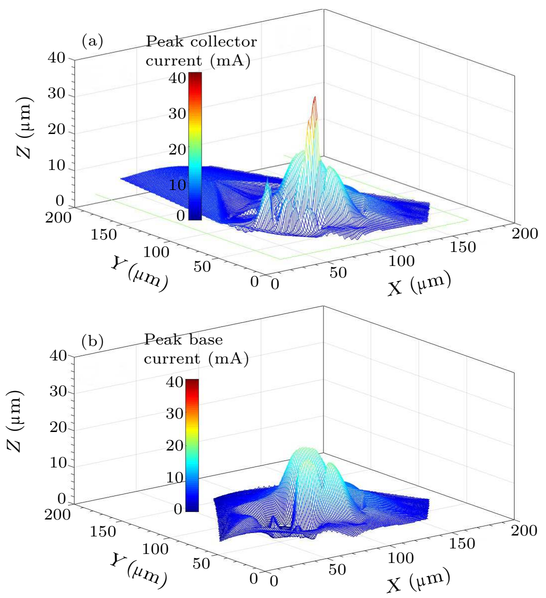

Fig. 6. (a) The 3D view of peak current during the laser micro-beam irradiation for collector. (b) The 3D view of peak current during the laser micro-beam irradiation for base.

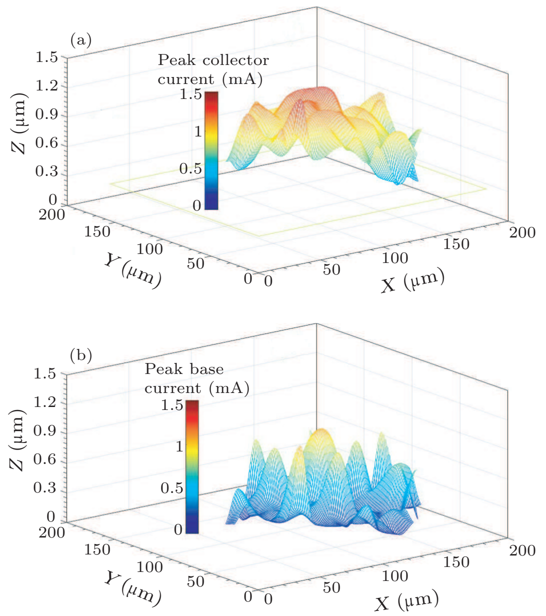

Fig. 7. (a) The 3D view of current transient peaks under heavy ion micro-beam irradiation for collector. (b) The 3D view of current transient peaks under heavy ion micro-beam irradiation for base.

Figures 6 and 7 plot the 3D view of peak currents, measured as functions of the laser and heavy ion micro-beam spot position. The scans produce approximately 250 data points based on an mV trigger on the base and collector. Coupling this micro-beam information with the peak transient current enables position correlation of the micro-beam strikes to the SiGe HBT's physical structures. As observed in laser testing results, the peak base and collector responses are confined to the base-collector junction. However, the sensitive area of peak current for heavy ion test is not very obvious because of the large beam spot and the ion scattering. It can be seen that the peak values of collector current in Figs. 6 and 7 are higher than that of base current, significantly indicate that the nature of the current transient is controlled by the behavior of the C/S junction. As observed in 3D view of Fig. 7, the peak current responses are confined to the sensitive area, which is located on the X-axis from 80 to 120 μm and from 40 to 90 μm on the Y-axis, just corresponding to the area of the C/S junction.

In summary, we have performed pulsed laser and heavy ion micro-beam on KT9041 SiGe HBT. The current transients induced by pulse laser and heavy ion have the same waveform and total duration time, and the peak current transients all mainly concentrated on the C/S junction. The dependence of laser energies and voltage biases has shown that the amplitudes of current transients vary with the energies and the biases, while the waveform remains unchanged. The sensitive area of the SEE for the SiGe HBT is obtained by using micro-beam data to the position-correlate current transients, which shows that the charges collected by the terminals are strong function of the ion striking position and most of the electrons and holes are collected by the collector and substrate terminals, respectively. The laser pulse and heavy ion induced current transient data represent a significant improvement to understanding of current transients and charges collection in SiGe HBTs by using micro-beam data to position correlation.

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