RAPID COMMUNICATION

A single-event transient induced by a pulsed laser in a silicon–germanium heterojunction bipolar transistor*

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A study on the single event transient (SET) induced by a pulsed laser in a silicon–germanium (SiGe) heterojunction bipolar transistor (HBT) is presented in this work. The impacts of laser energy and collector load resistance on the SET are investigated in detail. The waveform, amplitude, and width of the SET pulse as well as collected charge are used to characterize the SET response. The experimental results are discussed in detail and it is demonstrated that the laser energy and load resistance significantly affect the SET in the SiGe HBT. Furthermore, the underlying physical mechanisms are analyzed and investigated, and a near-ideal exponential model is proposed for the first time to describe the discharge of laser-induced electrons via collector resistance to collector supply when both base–collector and collector–substrate junctions are reverse biased or weakly forward biased. Besides, it is found that an additional multi-path discharge would play an important role in the SET once the base–collector and collector–substrate junctions get strongly forward biased due to a strong transient step charge by the laser pulse.

Keywords: single event transient (SET), pulsed laser, charge collection, SiGe heterojunction bipolar transistor (HBT)

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1. Introduction

Degradation and failure caused by radiation damage[1–8] are major challenges when semiconductor devices operate in a space radiation environment. Silicon–germanium (SiGe) heterojunction bipolar transistor (HBT) and bipolar complementary metal oxide semiconductor (BiCMOS) technologies have offered some compelling advantages in the field of radio-frequency (RF), analog, and mixed-signal circuit applications by combining high performance with high integration density and low cost.[4,5] Previous studies demonstrated an excellent multi-Mrad tolerance of SiGe HBTs to both displacement damage and total ionization dose radiation without intentional hardening,[3,9,10] making them attractive for radiation-rich space applications. The single event effect (SEE), however, is a serious problem for SiGe HBTs and further complicated by many factors, such as particle species and energy, incidence position and angle, bias condition, and load resistance.[11–13] Particularly, research on the effect of load resistance on the single event transient (SET) in SiGe HBTs are relatively rare, with few experimental data reported up to now, despite some simulation studies.[14,15] Because of its non-destructive nature and accurate positioning, the pulsed laser microbeam has been shown to be an effective tool in an attempt to better understand the origin of the SET in microelectronic devices and circuits.[16,17] The pulsed laser can reproduce the transient behavior similar to that observed during energetic particle testing. The photon energy defines the amount of carriers generated in the semiconductor. Although the mechanism of carrier generation and distribution induced by a pulsed laser differs from that by a heavy ion, the effects of charge collection are similar for the two cases.

In this paper, we present a comprehensive investigation on the SET in SiGe HBTs by means of pulsed laser microbeam. The front side of the device under test (DUT) is irradiated with varying laser energies and different load resistances. Measurement results show that the waveforms of the SET and charges collected by the collector supply are strongly dependent on the laser energy and load resistance. The underlying physical mechanisms are analyzed and investigated, and a near-ideal exponential discharge model is proposed for the first time to describe the collection of the laser-induced electrons via collector load resistance by collector supply when both base–collector (BC) and collector–substrate (CS) junctions are reverse biased or weakly forward biased.

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2. Experiment

The DUT in this study is a SiGe HBT, which is designed and fabricated by Institute of Microelectronics, Tsinghua University, and the cross section is shown in Fig. 1. This SiGe HBT has a quasi-self-aligned emitter-based structure with a polysilicon emitter contact, ion implanted extrinsic base, and local oxidation of silicon (LOCOS) isolation. The key fabrication processes are described as follows: after n^+ buried layer (NBL) formation on the p-type substrate, the 0.8-μm n^- epitaxy is completed. An n^+ collector sinker is then forms the lead collector to the surface, followed by selectively implanted collector (SIC), 120-nm insituboron doped graded SiGe base epitaxy (maximum Ge component of about 15%), and a heavily doped n^+ polysilicon emitter contact. The emitter and substrate are connected together via metal interconnection. An interdigital layout is adopted for the chip design, which is composed of four emitter fingers with dimension of 0.4×20 μm^2 for each finger. The DUT chip is mounted in a metal–ceramic package with the package lid removed for the laser irradiation.

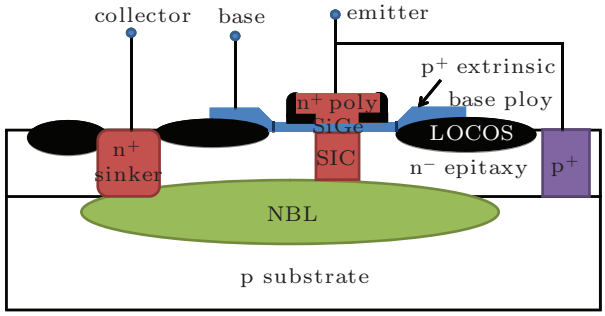


Fig. 1. (color online) Cross section of the SiGe HBT under investigation.

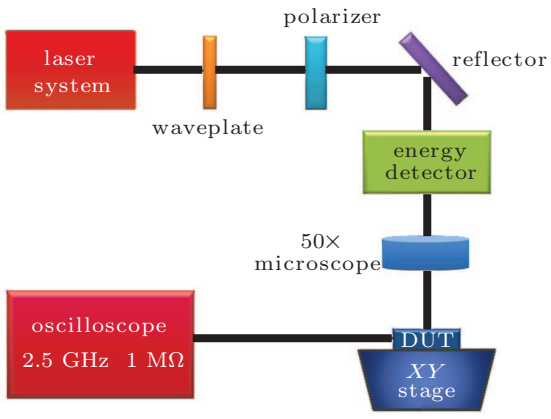


Fig. 2. (color online) Experimental setup for the pulsed laser SET measurement.

Laser microbeam irradiation was performed at the Center for Space Science and Applications, Chinese Academy of Sciences. The DUT was fixed on a *xyz* stage, which controls the position and focus of the incident pulsed laser microbeam. The optical setup is similar to those described in Refs. [16] and [17], as shown in Fig. 2. A combination of waveplate and polarizer varies the energy of pulsed laser, detected by the flowing energy detector. A 50X microscope is applied to focus the laser beam on the front side of the DUT, producing a laser pulse spot with diameter of about 2.0 μm. The DUT is irradiated by the laser microbeam with pulse width of 25 ns, repetition rate of 1 kHz, and wavelength of 1064 nm. A 2.5-GHz Tektronix oscilloscope with 1 MΩ impedance is used to detect and record the SET. The DUT, connected in a common-emitter configuration, as shown in Fig. 3, is irradiated with both emitter and base grounded, and collector bias voltage fixed at $V_{CC} = 2$ V through a load resistor R_c, where CS and Cs denote parasitic CS diode and CS capacitor, respectively.

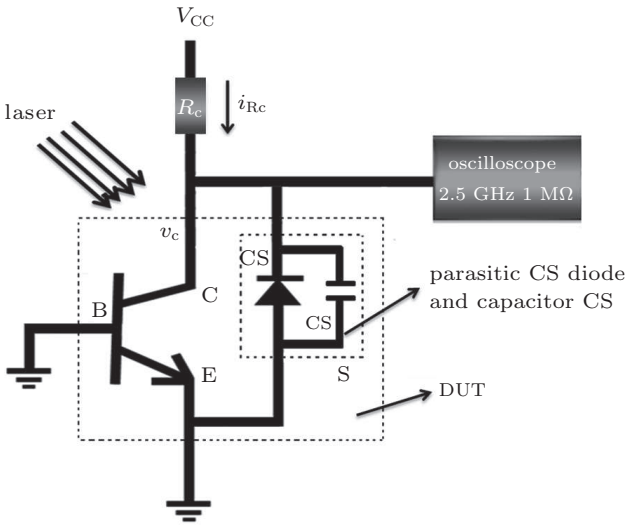


Fig. 3. Schematic diagram of common-emitter test configuration where a 2.5-GHz sampling oscilloscope is used to visualize and record the SET in SiGe HBT.

3. Results and discussion

3.1. Laser energy dependence

The SiGe HBT loaded with R_c of 10 kΩ is irradiated by the pulsed laser with energy ranging from 2.05 to 22.4 nJ. The SET pulses are captured at collector terminal by the digital sampling oscilloscope. The pulsed laser generates photons with energy above Si band gap such that they are absorbed and then numbers of electron-hole pairs (EHPs) are produced. Most of the electrons and holes in neutral regions recombine rapidly and only those in the space charge region of reverse biased pn junction, mainly the CS junction, will be separated and then collected by V_{CC} and ground, respectively. The transient voltage captured at collector terminal (v_c) and transient collector current calculated by $i_c = (V_{CC} - v_c)/R_c$, are shown in Figs. 4(a) and 4(b), respectively. The initial electron collection by V_{CC} will cause a transient upward-step current pulse and a transient downward-step voltage pulse, which is generally a picosecond-scale process and the details are not captured in this study. The varying laser energy is found not to

change the waveform of transient pulse, but a significant increase in the v_c drop and the peak i_c at the very beginning of the SET is observed with increasing laser energy until some critical value. Once the energy is larger than the critical value, 9.3 nJ in this case, both the starting v_c and the peak i_c begin to saturate, leading to a saturated starting v_c of about -0.8 V and a saturated peak i_c around 0.27 mA, which is consistent with the simulation results reported in Ref. [14].

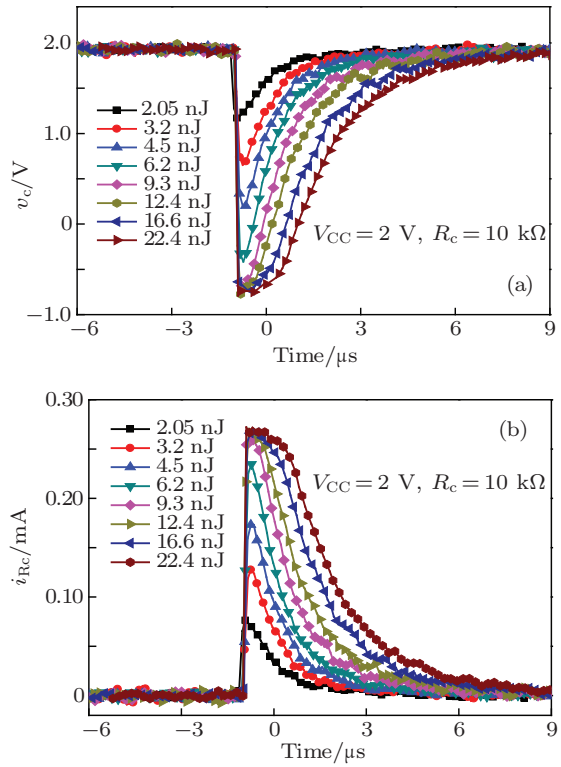


Fig. 4. (color online) (a) Transient collector voltage v_c and (b) transient collector current through R_c for different laser energies.

As the base bias is set as zero, the DUT operates at the off state over most of the period except when v_c is much lower than zero, and the EHPs are mainly discharged via R_c and collector–substrate capacitor (C_s). As long as CS junction is reverse biased or weakly forward biased and carrier recombination is neglected, C_s can be approximated to be roughly constant, so v_c will follow an ideal exponential law during the duration of discharging

$$v_c(t) = V_{CC} - [V_{CC} - v_c(0)]\,e^{-(t/\tau)}, \tag{1}$$

where $v_c(0)$ is the value of $v_c(t)$ at the beginning of discharge, and τ is the time constant for the ideal exponential charge. Rearranging Eq. (1) yields

$$\ln[V_{CC} - v_c(t)] = \ln[V_{CC} - v_c(0)] - \frac{t}{\tau}, \tag{2}$$

indicating that $\ln(V_{CC} - v_c)$ will vary linearly with discharging time, and τ can be determined by the linear regression slope of $-1/\tau$. The above exponential expression (1) is verified by the straight-line part of the curves shown in Fig. 5, where linear dependence of $\ln(V_{CC} - v_c)$ on discharging time is clearly observed for different laser energies. Obviously, the time period corresponding to the straight-line part of $\ln(V_{CC} - v_c)$ is the ideal exponential charge stage. The charge collected by V_{CC}, i.e., Q_c, and τ for different laser energies are shown in Fig. 6. The charge Q_c, calculated as a time integral of i_c, increases monotonically with increasing laser energy, and τ is roughly constant for lower laser energies, and then increases rapidly as the energy gets higher than 9.3 nJ.

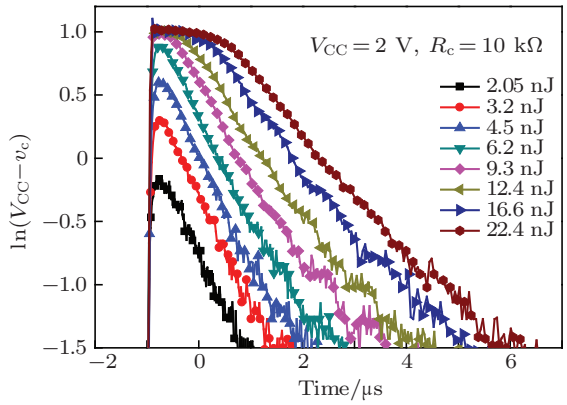


Fig. 5. (color online) Dependence of $\ln(V_{CC} - v_c)$ on discharge time for different laser energies.

When the laser energy is low, the laser-induced carrier density and i_c are so small that the voltage drop across R_c is not large enough to significantly forward bias either CS or BC junction. Under this condition, the electrons and holes generated in the space charge region of CS junction are separated and only collected by V_{CC} and ground through R_c and C_s, respectively. The SET can approximately be considered as a process of a laser-induced transient step charge followed by an ideal exponential discharge characterized by Eqs. (1) and (2). From Fig. 4, it can be seen that as long as the laser energy is set below the critical value of 9.3 nJ, the higher the energy is, the larger the initial peak i_c is, and thus the larger the starting drop in v_c is. When the laser energy is large enough to make the starting v_c drop to about -0.8 V, both CS and BC junctions will be strongly forward biased, driving the SiGe HBT into reversely active operation. Under these bias conditions, the electron collection via R_c by V_{CC}, on one hand, is shunted by the reverse-operated SiGe HBT to emitter and base, as claimed in Ref. [14], on the other hand, is compensated by the electron injection to substrate through the forward biased CS diode, which was not mentioned in Ref. [14]. Note that substrate, emitter, and base are all grounded here. Therefore, as the laser energy increases, over 9.3 nJ in this work, as a result of a dynamic equilibrium among electron generation by the pulsed laser, electron collection by V_{CC} and ground, and electron recombination with holes, the initial peak i_c becomes saturated, and thus the starting v_c is clamped at about -0.8 V.

Further inspection of Figs. 4 and 5 indicates that for the laser energies higher than 9.3 nJ, a stage of multi-path electron discharge (besides V_{CC} via RC, the electrons are also collected by ground through the reverse-operated SiGe HBT and the forward biased CS diode) is inserted between the transient step charge and the single-path ideal exponential discharge (to V_{CC} via R_c only). During the multi-path discharge stage, v_c will increase slowly until the BC and CS junctions recover to be weakly forward biased and even reverse biased, beginning the ideal exponential discharge stage.

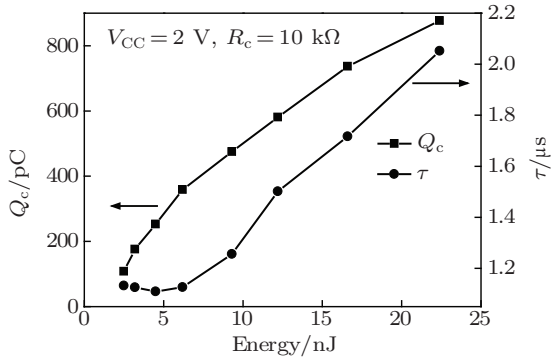


Fig. 6. Charge collected by V_{CC} and time constant τ as functions of laser energy.

As the laser energy goes up, the i_c pulse amplitude increases for the energies lower than 9.3 nJ, and the width increases despite of the saturated plateau for the energies higher than 9.3 nJ, as can be seen in Fig. 4(b). Therefore, the time integral charge Q_c increases monotonically with the laser energy, as shown in Fig. 6. As for the discharge time constant, τ is approximately equal to the product of R_c and C_s in this case, so it keeps nearly unchanged for the laser energy lower than 9.3 nJ due to the negligible change of C_s with reverse CS bias voltage. However, once the laser energy is larger than 9.3 nJ, the CS junction is initially driven to be strongly forward biased, initiating the multi-path discharge. Then, the CS junction turns gradually back to be weakly forward biased and even reverse biased, switching to an ideal exponential discharge with a time constant τ. If $\tau \approx R_C C_S$ still holds, it is found that the C_s will increase monotonically with laser energy. The reason for this is that a plausible hypothesis might be given below. Suppose some minority traps could be produced by the laser irradiation, and then during the multi-path discharge stage some minority carriers are injected due to the forward biased CS junction and might be captured by the traps. After entering the ideal discharge phase, the captured carriers might be released as CS junction returns from forward bias toward reverse bias. The trapping and releasing of the part of minority carriers with varying CS junction bias voltage would result in an additional trapping capacitor, which, in parallel with the CS junction capacitor, would increase C_s. Moreover, the higher the laser energy is, the more traps may be created, and the higher trapping capacitance would contribute to C_s. Therefore, the increase in time constant τ with increasing energy larger than 9.3 nJ may be explained this way. Of course, the underlying physical mechanisms need to be further justified and explored.

3.2. Load collector resistance dependence

Transient pulses at laser energy of 11.4 nJ are captured for different R_c from 200 Ω to 100 kΩ in the SiGe HBT. The changes of v_c and i_c with time for different R_c is shown in Figs. 7(a) and 7(b), respectively. The results clearly show that the SET pulse highly depends on the load resistance R_c. Similar to the case of the laser energy effect as shown in Fig. 4(a), the initial v_c drop rises from 0.75 V for 200 Ω to 2 V for 1 kΩ with R_c increasing, then the starting v_c becomes saturated and clamped at about −0.8 V when the CS and BC junctions become strongly forward biased for R_c over 5.1 kΩ. Transient current i_c, however, shows a rapid decrease with increasing R_c in spite of increasing voltage drop across R_c, as shown in Fig. 7(b).

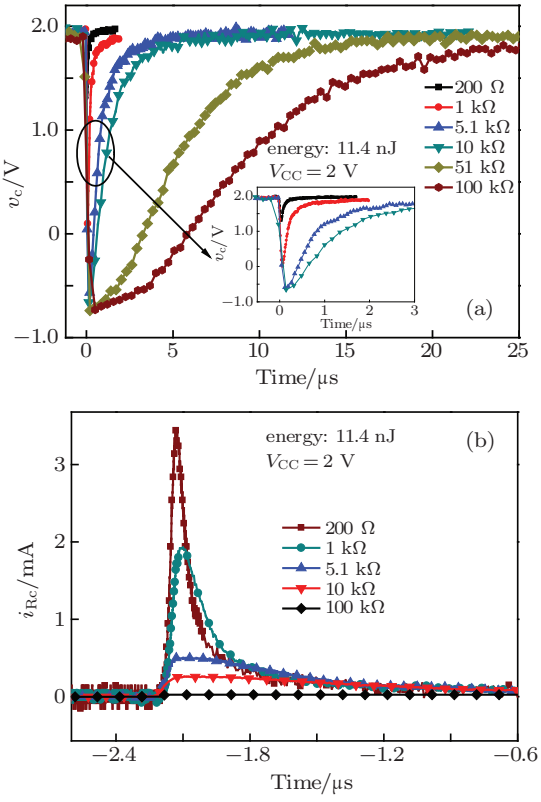


Fig. 7. (color online) (a) Transient collector voltage v_c and (b) transient collector current through R_c for different R_c.

Similar to the laser energy effect, the near-ideal single-path exponential discharge phase, where $\ln(V_{CC}-v_c)$ decreases approximately linearly with discharge time at a slope of $-1/\tau$, also exists for different R_c, and an additional multi-path discharge stage is also present before the near-ideal discharge for R_c larger than 5.1 kΩ, as shown in Fig. 8.

By calculating the linear regression slope of $\ln(V_{CC} - v_c)$ versus time in the near-ideal discharge stage in Fig. 8 and integrating i_c over time in Fig. 7(b), respectively, both τ and Q_c as functions of R_c are plotted in Fig. 9. Regarding the time constant, τ is found to increase with increasing R_c, verifying the relation of with the linear-fitting slope of τ versus R_c giving the approximate value of the reverse biased C_s. As to the charge collected by V_{CC}, Q_c is shown to hardly change in the range from $R_c = 200\ \Omega$ to 1 kΩ, and then decrease as R_c further increases.

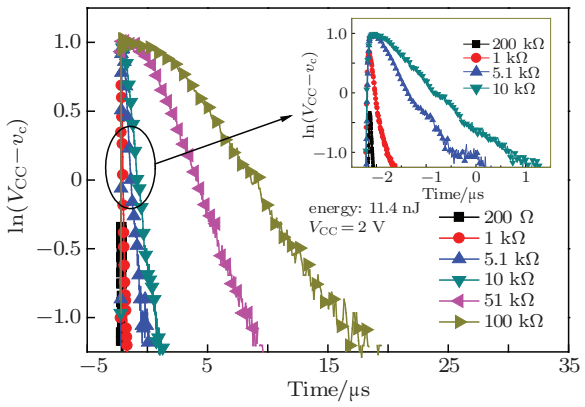


Fig. 8. (color online) Dependence of $\ln(V_{CC} - v_c)$ on discharge time for different R_c

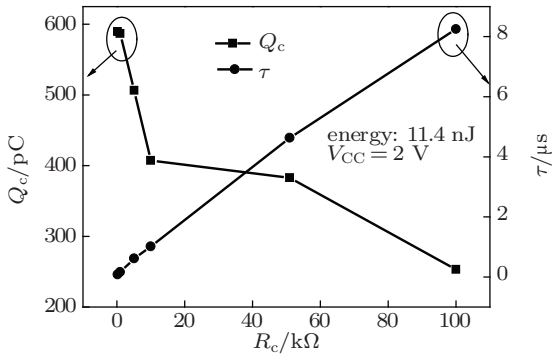


Fig. 9. Charge (Q_c) collected by V_{CC} and time constant τ as functions of R_c.

In order to explain the Q_c variation with R_c, different discharge modes for the varying R_c should be considered. When R_c is so small ($R_c = 200\ \Omega$ and 1 kΩ here) that neither CS junction nor BC junction can be strongly forward biased, and thus the laser-induced electrons can only be collected by V_{CC} through the near-ideal discharge process. As long as recombination can be neglected due to the weak forward bias or reverse bias for all pn junctions concerned, the amount of the laser-induced carriers available for the discharge should be a constant, so Q_c is approximately equal for $R_c = 200\ \Omega$ and 1 kΩ. As can be seen from Fig. 7(b), when R_c increases from 200 Ω to 1 kΩ, the width of i_c pulse is actually widened though the pulse amplitude is lowered remarkably, leading to almost the same time integration of i_c, i.e., Q_c. As a large R_c ranging from 5.1 kΩ to 100 kΩ is used, the additional multi-path discharge stage will precede the near-ideal discharge process. It is the multi-path discharge that makes a difference in the observed Q_c decrease with increasing R_c from 5.1 kΩ to 100 kΩ. On the one hand, during the multi-path discharge stage, there exist three competitive electron discharge paths, i.e., the electron collection via R_c by V_{CC}, the electron shunting by the reverse operated SiGe HBT to ground, and the electron injection to ground through the strongly forward biased CS junction. The first path with larger R_c would obviously present higher impedance compared with the other two paths, thus less electrons would pass through R_c and are collected by V_{CC}eventually. On the other hand, a larger R_c leads to longer discharging time and more electrons, which would have been collected by V_{CC} and tend to annihilate via recombination with holes[15,18] because of the strong forward bias of the CS junction in the course of the multi-path discharge. For a logic inverter with load resistor R_c shown in Fig. 3, based on the above analysis, it is interesting to observe that a larger R_c with a less charge collection results in a longer (worse) duration of the collector voltage upset, experimentally confirming the simulation results in Ref. [14].

4. Conclusions

The effects of laser energy and collector load resistance R_c on the SET induced by a pulsed laser in an off-state SiGe HBT are investigated in detail. Two different discharge modes for the SET pulse are identified depending on the laser energy and R_c. For lower energy at a fixed R_c, the SET pulse can be considered as a transient step charge followed by an ideal exponential discharge with a time constant $\tau = R_c C_s$. As the laser energy increases, both the starting drop in collector voltage (v_c) and the transient collector current i_c through R_c increase, and τ keeps nearly unchanged. Once the laser energy rises up to a critical value, the starting v_c will be clamped at about -0.8 V and an additional multi-path discharge stage will precede the ideal exponential discharge, and τ is found to increase rapidly with the laser energy. The charge Q_c collected by V_{CC} via R_c increases monotonically with the laser energy. Similar to the energy dependence, the multi-path discharge also exists for R_c higher than a critical value. The Q_c hardly changes for small R_c and then drops with further increasing R_c due to increased shunt by reverse operated SiGe HBT, enhanced compensation by forward injection of CS diode, and prolonged duration for carrier recombination. For an RC product, τ gets larger with increasing R_c under this condition.

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