Single-Event Effects in Microelectronics Induced by Through-Wafer Sub-Bandgap Two-Photon Absorption

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Abstract

Carrier generation based on nonlinear absorption in semiconductors has become an important tool for the investigation of single-event effects in modern microelectronic devices. Recent advances and the present status of two-photon absorption induced single-event effects interrogations are described.

1. Introduction

Electronic systems operating in space are exposed to radiation in the form of energetic charged particles, such as protons and heavy ions. When a single charged particle passes through the semiconductors and insulators that make up an integrated circuit (IC), it liberates electrons from the constituent atoms. These carriers can disturb the normal operation of the IC, causing a variety of different and potentially harmful effects that are referred to as single-event effects (SEEs). SEEs are of great concern because they may lead to a loss of information, functional interruptions, physical failures or, in the worst case, to a total loss of control of the spacecraft. In space, heavy ions responsible for SEEs originate from solar flares and cosmic rays, or from proton-induced reactions in low earth orbit. In addition, ions resulting from the interaction of atmospheric neutrons with the silicon and boron atoms in electronic circuits themselves have become a threat for modern advanced technologies, even at ground level.

Over the past two decades, picosecond pulsed lasers operating in the visible and near-infrared regions of the spectrum have become essential tools for evaluating the SEE susceptibility of microelectronic devices by injecting carriers at well-defined locations, permitting detailed studies of single-event effects that are not possible with other ionization sources. Such approaches, however, are based on Beer’s Law absorption, and are severely limited by the multiple metallization layers that are characteristic of modern semiconductor technologies.

To alleviate this problem, and permit carrier injection through the wafer from the back-side of the device, a new method of carrier generation based on two-photon absorption (TPA) has been developed and demonstrated [1-3]. This method is based on nonlinear absorption at sub-bandgap optical wavelengths using high peak-power femtosecond laser pulses. For two-photon absorption processes to dominate carrier production, the laser wavelength is chosen to be less than the bandgap of the semiconductor material. Under this condition no carriers are generated at low light intensities. At sufficiently high irradiances the material can absorb two (or more) photons simultaneously, to generate a single electron-hole pair. Because carrier generation in the two-photon process is proportional to the square of the laser pulse intensity, significant carrier generation occurs only in the high-intensity focal region of the focused laser pulse. This enables charge injection at any depth in the structure, permits three-dimensional mapping of the SEE sensitivity of a device, and backside illumination of circuits fabricated on silicon wafers. The two-photon method represents a novel approach to SEE evaluation that provides insights that are not accessible with other techniques, and places a renewed emphasis on obtaining a detailed understanding of semiconductor nonlinear-optical properties that can exert a significant influence on the propagation and absorption of ultrashort laser pulses. Over the past few years the through-wafer TPA SEE approach has become the method of choice for evaluating single-event effects in state-of-the-art micro- and nano-electronic circuits.

This paper presents experimental results illustrating the utility of the through-wafer TPA approach for basic mechanisms studies. We focus here on the charge-collection transients induced in a silicon-germanium heterojunction bipolar transistor (SiGe HBT).

2. Results and Discussion

2.1 Experimental

The single-event upset and single-event transient experiments at wavelengths below the silicon bandgap were performed using an amplified titanium sapphire laser system (Clark-MXR CPA 1000) that pumps a tunable optical parametric amplifier and produces nominally 120 fs optical pulses at 1.26 μm with about 100 μJ of energy per pulse. The strong IR beam is attenuated by a waveplate-polarizer combination to precisely control the pulse energy incident on the device under test (DUT). The pulse energy is monitored with a calibrated large area InGaAs photodiode. The DUT is mounted on a motorized x-y-z translation platform with 0.1 μm resolution, and the optical pulses are focused through the wafer onto the front surface of the DUT with a 100 microscope objective, resulting a near-Gaussian beam profile with a diameter of 1.4 μm at focus [1]. Because the carrier deposition varies as I^2, this corresponds to a carrier density distribution with a 1.0 μm diameter (full-width-at-half-maximum). All experiments are performed at room temperature (295 K). The DUT is imaged through the wafer using near-infrared (NIR) imaging optics in conjunction with an InGaAs focal plane array.

2.2 Results

When two-photon absorption is the primary means of carrier generation, the optical loss and penetration depth can be deterministically manipulated: because carrier generation is proportional to the square of the laser pulse irradiance, the generated carriers are highly concentrated in the high-irradiance region near the focus of the beam, as is illustrated in Fig. 1 [1],[4-5]. For a material that is transparent to the incident radiation, the high irradiance region can be directed to any depth in the material by translation of the device under test (DUT) with respect to the focusing element. This characteristic permits three-dimensional mapping of single-event effects, and backside, through-wafer irradiation of devices. The ability to interrogate SEE phenomena through the wafer using backside irradiation was a primary motivating factor for development of the TPA SEE technique. Backside irradiation eliminates interference from the metallization layers, and circumvents many of the issues associated with testing flip-chip mounted parts. A photograph of a flip-chip mounted device illustrating the back-side wafer access and a schematic diagram illustrating the through-wafer, backside TPA approach is shown in Fig. 1.

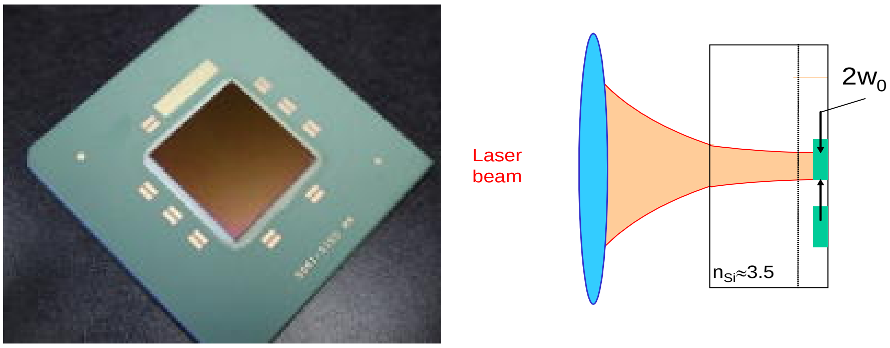

Figure 1. Photograph of a flip-chip packaged silicon device and schematic diagram illustrating the through-wafer two-photon absorption approach.

A wide variety of device types have been evaluated using the through-wafer TPA approach. This summary describes transient charge-collection measurements performed on silicon-germanium heterojunction bipolar transistors (SiGe HBTs). Considerable effort and resources have been expended to investigate the viability of SiGe HBTs for space applications because they provide full integration with commercial silicon CMOS, they enable system-on-a-chip (SoC) applications, they have speed and switching characteristics similar to III-V technologies, and they offer high levels of inherent total ionizing dose tolerance. However, despite these encouraging characteristics, circuits designed with SiGe HBTs can suffer from unacceptably high levels of single-event upsets (SEUs), manifested in high-speed serial data applications as burst errors that present an extreme SEU hazard for applications operating at Gbit/s data rates where the bit period is greater than 1 ns. Direct measurements of the ionization-induced current transients are necessary to calibrate TCAD tools for model development and evaluation of the basic mechanisms of carrier transport and collection in HBT structures, leading to a better understanding of circuit- and system-level SEE effects.

The experimental results presented here were obtained from a SiGe HBT test structure from the IBM 5AM BiCMOS process technology, which has a single emitter stripe with dimensions of 0.5 μm by 2.5 μm. The deep trench isolation surrounding the active device has outer dimensions of 6.2 μm by 6.4 μm and inner dimensions of 4.1 μm by 4.3 μm. The depth of the deep trench isolation is between 7 and 8 μm. The n+/p−

subcollector-substrate junction resides in the area enclosed by the deep trench isolation. Figure 2 shows a cross section of an IBM SiGe HBT device, illustrating the device structure as is largely defined by the deep-trench isolation. Figure 3 shows representative base and collector transients measured for two different bias conditions. The data of fig. 3 illustrate the general characteristics of the ionization-induced transients for this technology. Single-transistor data of this type are used to calibrate and validate TCAD models, which then can be used for predictive purposes in complex circuits and systems.

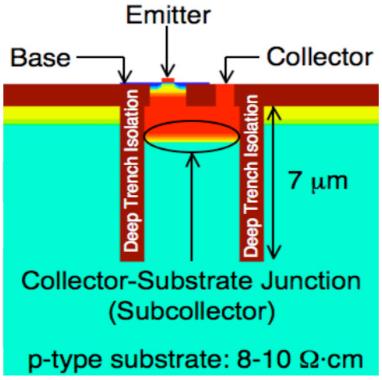

Figure 2. TCAD cross section of an IBM 5AM SiGe HBT. The three process features relevant to transient production and charge collection are the deep trench isolation, the subcollector-substrate junction, and the lightly doped p-type substrate.

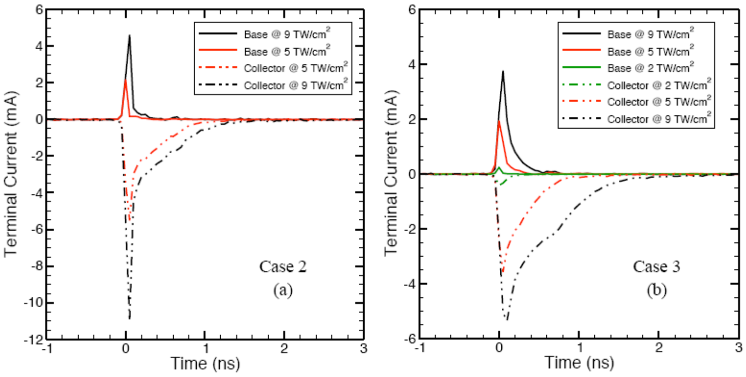

Figure 3. Base and collector current transients for (a) Case 2 (V_C = 3 V) and (b) Case 3 (V_{Sub} = -3 V). In all cases the beam focal point was at the device surface and focused to a diameter of 1.6 μm. Note the different y-axes on each of the charts. In each case, the base transients are largely unaffected. The Case 2 collector transients are up to 2x larger than their Case 3 counterparts.

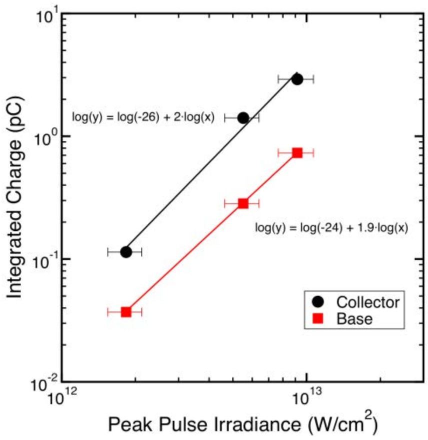

Figure. 4. Plot of integrated charge vs. the peak pulse irradiance measured for a bias of -4 V on the substrate with all other terminals grounded. These data serve to verify the quadratic character of the observable, and the two-photon absorption origin of the carrier generation.

Figure 4 shows a plot of integrated charge vs. the peak pulse irradiance measured for a bias of -4 V on the substrate, with all other terminals grounded, verifying the quadratic character of the observable, and the TPA origin of the carrier generation. Figure 5 shows a series of two-dimensional maps of the TPA-induced current transient amplitude for through-wafer irradiation. The data of fig. 5 illustrate that the primary charge-collection region is localized within the confines of the deep trench isolation. The measurements shown in figs. 3-5 are for charge localization near the surface of the device. Measurements also have been performed as a function of the depth (z) below the surface, illustrating the significant effects of long-range diffusion and potential collapse in these devices.

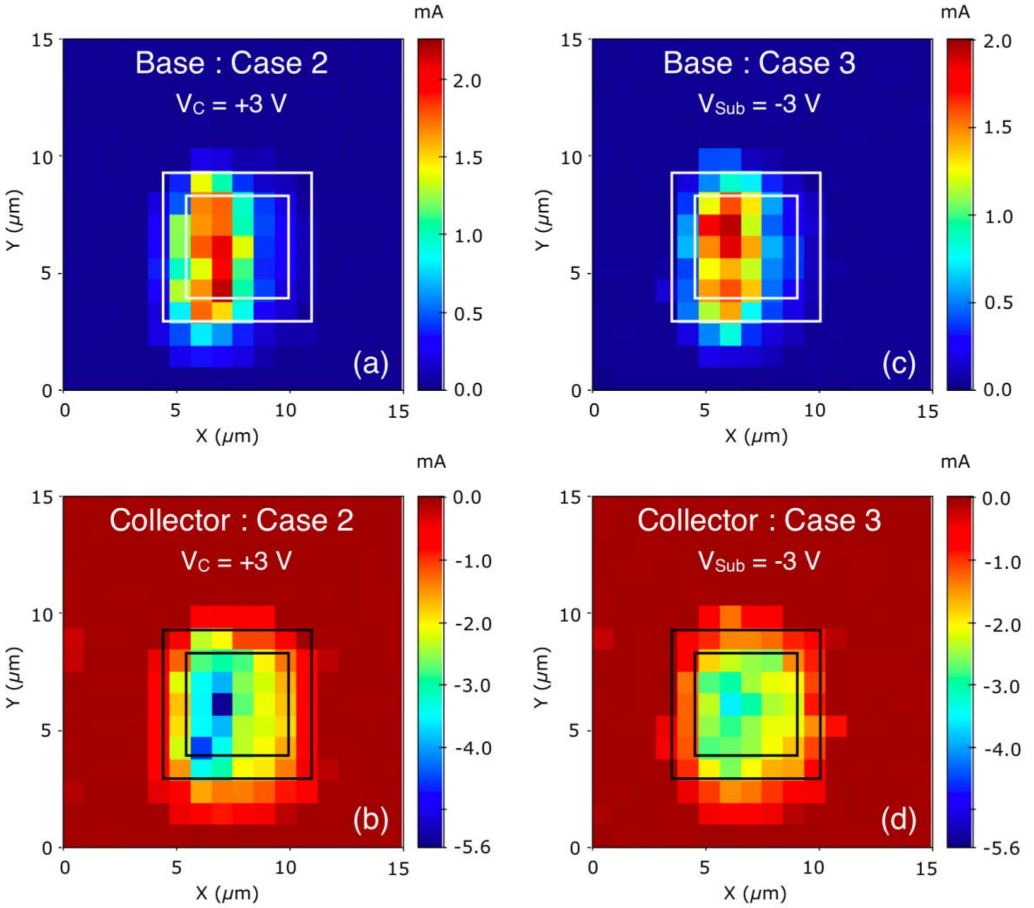

Figure 3. X-Y charge-collection maps show the maximum current-transient magnitude for carrier generation by TPA for an IBM 5AM SiGe HBT for bias conditions indicated. The laser was focused at the device surface to a diameter of approximately 1.6 μm; with the position incremented in 1 μm steps for all cases. The geometry of the deep trench isolation is overlaid on all four images for reference.

3. Conclusions

This report describes the fundamental aspects of the through-wafer TPA SEE approach for single-event effects studies, with application to measurement of the charge-collection transients for a SiGe HBT device. The results illustrate the utility of the TPA SEE approach for basic mechanisms investigations. Additional details of the SiGe study can be found in [6].

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