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Comparison of Effects of Ionizing Radiation and High-Current Stress on Characteristics of Self-Aligned Bipolar Transistors

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The effects of high forward-current stress and ionizing radiation on the emitter-base junction characteristics of advanced self-aligned bipolar transistors were investigated and compared in this study. Both high-current stress and x-ray irradiation caused the base current to increase substantially in the low bias regime, resulting from the generation of interface-states. The "activation energy" of the induced interface-states was found to be strongly dependent on the emitter-base bias for the current-stressed devices and to be relatively insensitive to the emitter-base bias for the x-ray irradiated devices.

INTRODUCTION

Recent progress in advanced self-aligned bipolar technology has resulted in high-performance ECL circuits with sub-75ps gate delays (1-5). To achieve such high performance, advanced bipolar devices generally have thin bases, shallow emitters, and, in particular, reduced parasitics. The method for reducing bipolar device parasitics is to self-align the contact of the poly-emitter to the poly base contact. Consequently, the emitter-to-base contact separation in self-aligned transistors is only the thickness of a sidewall spacer oxide, and the perimeter of the emitter-base junction is located underneath the sidewall oxide as shown in Fig.1. As a result, the electrical characteristics of the emitter-base junction can be strongly influenced by the characteristics of the interface between the silicon and the sidewall oxide. Bipolar device scaling theory (6) suggests that the device current must be kept approximately constant in scaling in order to achieve scaled circuit performance. Therefore, the current density increases rapidly with decreased device size in high-performance bipolar devices. It has been shown (7) that when these advanced bipolar devices are operated at sufficiently high current densities, their characteristics could degrade. It was further suggested that surface-state generation could be the cause of the device degradation (7). It is well known that interface-states can be generated if the oxide/silicon interface is exposed to such radiative processing steps as x-ray lithography, reactive ion etching, e-gun metal evaporation, and plasma CVD deposition, which are required in VLSI chip fabrication (8). In this paper, we compare the surface-state characteristics due to high-current density stress with those due to x-ray irradiation.

EXPERIMENT

The experimental devices used in this study are basically identical to the self-aligned n-p-n transistors reported previously (3)(9). The transistors were mounted on high-temperature ceramic packages throughout the experiments and characterized in a nitrogen ambient at each controlled temperature. The irradiation source was an x-ray beam generated from a tungsten target bombarded by 40 KeV electrons. For this study, the devices were exposed to a dose of higher than 4.0×10^7 rads(Si). For the high-current stress, the transistors were kept at 280 °C and biased in the forward active mode by forcing a constant current density of 1 mA/μm^2 through the emitter. Such current density is quite typical of submicron ECL designs. The emitter-base junction characteristics at temperature between 90 °K and 300 °K were measured before and after x-ray irradiation and current-stress.

RESULTS AND DISCUSSION

Figure 2 shows the Gummel plot of a device before and after high high-current stress. The figure shows that the initial characteristics of the device is nearly ideal. However, the base current increases substantially in the low bias regime after high-current stress. The characteristics of the x-ray irradiation case, shown in Fig.3, are similar to those in Fig.2 for the high-current stress case. Since it is well-known that interface-states can be generated if the oxide/Si is exposed to ionizing radiation (8), it is likely that the excess current in both cases were caused by interface states. It should be pointed out that both devices have a measurable pre-existing tunneling current component in the emitter-base junction which was verified by the temperature dependence of the reverse-bias current as reported previously (10). It should also be emphasized that the tunneling junction (emitter/extrinsic base junction) is located underneath the sidewall oxide region (see Fig.1). Devices with the pre-existing tunneling component were purposely chosen in order to highlight the base current increase through the effect of interface-state-assisted tunneling. Figures 4 and 5 show the temperature dependence of the emitter-base junction currents of the high-current-stressed and the x-ray-irradiated devices, respectively. As shown in the figures, the diffusion component is dominating the junction current at higher bias while the excess current component is dominating at lower bias. The substantial increase of the base current in such devices significantly degrades the current gain at low voltages.

A number of possible mechanisms could be responsible for the excess current. Among them are the increase of the the surface recombination current and the onset of surface and/or bulk defect assisted tunneling current. Although interface states are generated during either high-current stress or x-ray irradiation, the resulting increase in surface recombination is not great enough to explain the magnitude of the excess current observed, because recombination current alone should give a base-current ideality factor no greater than two. Interface-state-assisted tunneling current seems to be a more plausible explanation.

The net excess current at low bias is plotted as a function of inverse absolute temperature in Figures 6 and 7, with V_{BE} as a parameter. Whereas, in the true forward-bias tunneling-current model (11), one expects the excess current to be relatively independent of temperature, Figures 6 and 7 show a temperature dependent excess current, implying that the excess current is not due to a pure tunneling process. The linear behavior suggests the association of an "activation energy" with each set of V_{BE} points. These activation energies suggest a picture where, after first tunneling into an interface state, a hole goes through some thermally activated emission process, probably moving from one interface state to another, or from one energy state to another, before finally recombining with an electron, and thus giving rise to the excess current. Physically, such a process is not unlike the optical/thermal process observed in many deep-level transients (12) where a carrier is first excited by a photon into an excited state and then thermally excited into a still higher state or into the conduction or valence band.

Note that there are two slopes in the case of x-ray irradiation, indicating that there are interface states with two different activation energies. The activation energies of the induced interface states deduced in this manner at different emitter-base bias are shown for both cases in Fig. 8. The activation energy of interface states generated by high-current stress is strongly dependent on the emitter-base voltage, as can be seen in the figure. On the other hand, the activation energies of interface states created by x-ray radiation are relatively insensitive to the emitter-base voltage.

If one interprets the x-ray-irradiated data by suggesting that x-ray irradiation generates surface states of two distinct energy levels, then the high-current-stress data suggests that only a narrow energy spectrum of surface-states was generated during high-current stress. However, these surface states assist tunneling in a field dependent manner.

Another possibility is that the x-ray irradiation generates a wide spectrum of surface states, as suggested by many MOS studies (6), although only two narrow bands of these states contribute significantly to the surface-state-assisted tunneling current in the forward-biased emitter-base junction. In this case the current-stress-induced surface states could have a much wider energy spectrum. It is interesting to note in this picture that the activation energies of the surface states generated by x-ray irradiation 'bracket' those generated by high-current stress.

CONCLUSIONS

The leakage current of emitter-base junction increases substantially in the low bias regime after either x-ray irradiation or high-current stress. It is clear that high-current stress causes device degradation through surface-state generation, although the surface states have somewhat different energy-spectral characteristics from those generated by x-ray-irradiation. As shown in this study, the oxide/Si interface plays a key role in the current characteristics of self-aligned bipolar transistors. It is therefore crucial to design self-aligned bipolar devices with a high quality oxide spacer to provide the devices with ideal characteristics and to insure long term device reliability.

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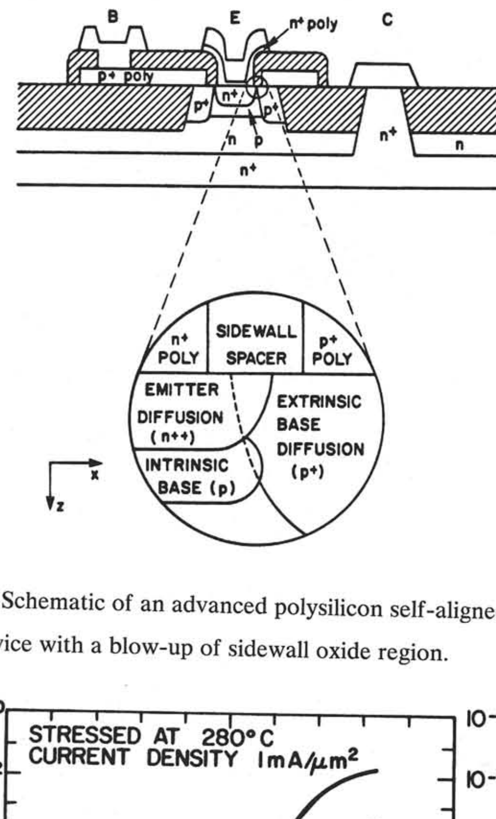

Fig.1 Schematic of an advanced polysilicon self-aligned bipolar device with a blow-up of sidewall oxide region.

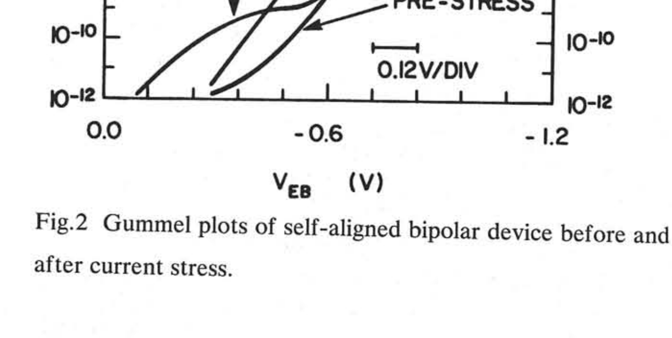

Fig.2 Gummel plots of self-aligned bipolar device before and after current stress.

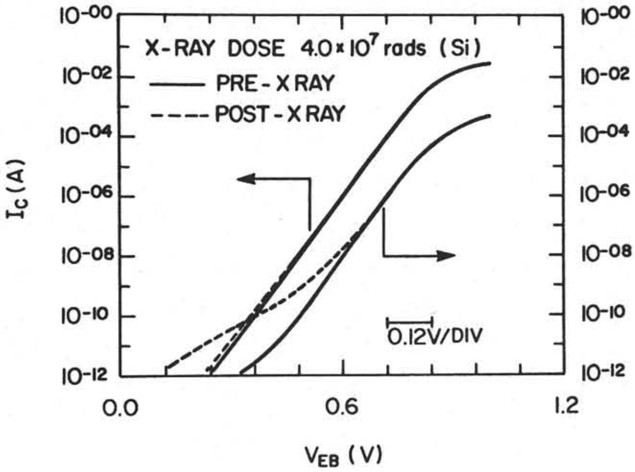

Fig.3 Gummel plots of self-aligned bipolar device before and after x-ray irradiation.

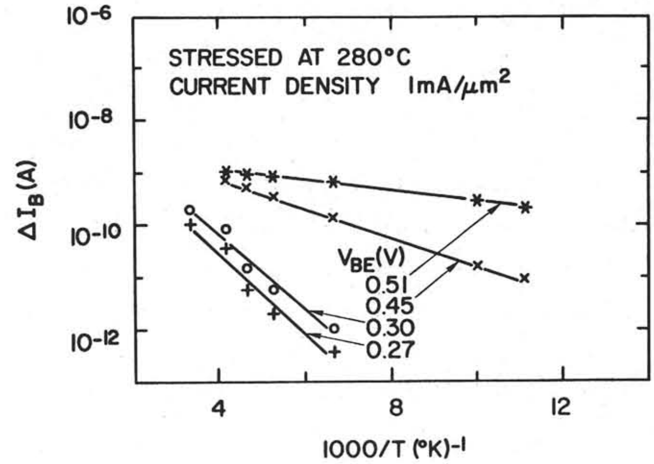

Fig.6 Net excess current versus 1/T for emitter-base junction after current stress.

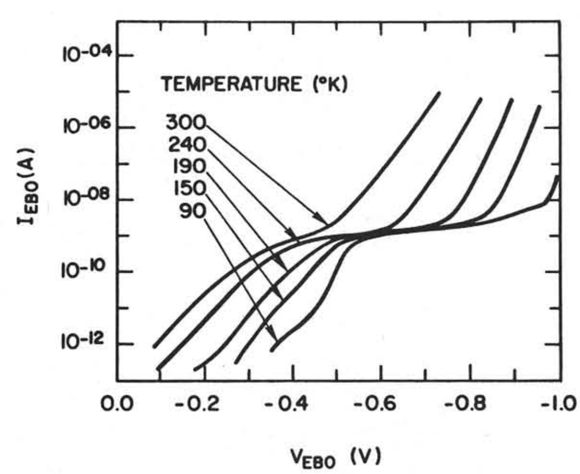

Fig.4 I_{EBO} versus V_{BE}at different temperatures for self-aligned bipolar device after current stress.

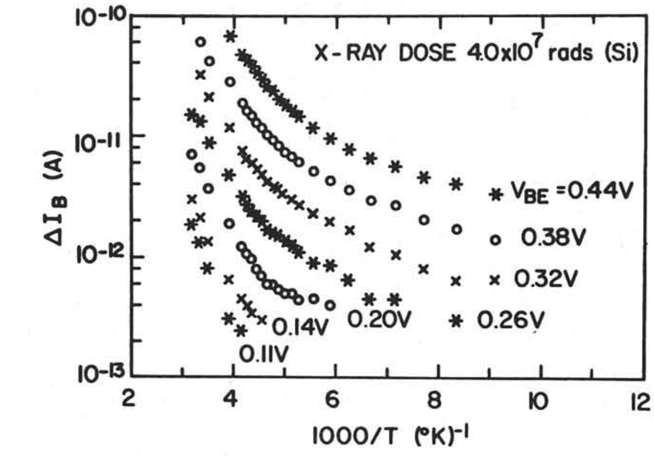

Fig.7 Net excess current versus 1/T for emitter-base junction after x-ray irradiation.

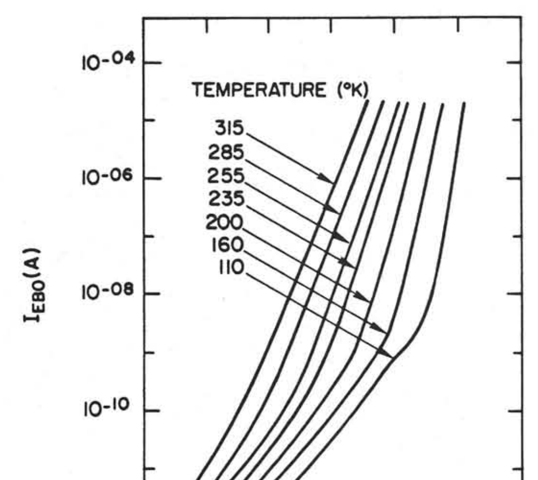

Fig.5 I_{EBO} versus V_{BE}at different temperatures for self-aligned bipolar device after x-ray irradiation.

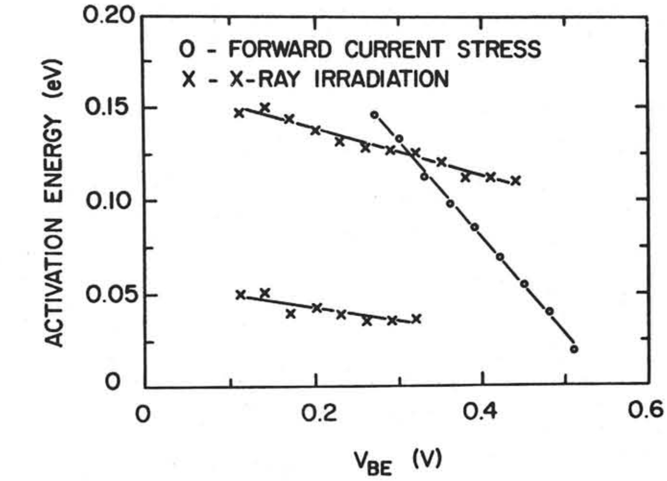

Fig.8 Activation energies of spacer-oxide/silicon interface states as a function of emitter-base voltage for devices after high-current stress and x-ray irradiation.