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Low-Frequency Noise and Deep Level Transient Spectroscopy in n-p-n Si Bipolar Junction Transistors Irradiated with Si Ions

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Abstract**—The properties of defects in *n-p-n* Si bipolar junction transistors (BJTs) caused by 17 MeV Si ions are investigated via current-voltage, low-frequency noise, and deep-level transient spectroscopy (DLTS) measurements. Four prominent radiation-induced defects in the base-collector junction of these transistors are identified via DLTS. At least two defect levels are observed in temperature-dependent low-frequency 1/*f* noise measurements, one that is similar to a prominent defect in DLTS and another that is not. Defect microstructures are discussed. Our results show that DLTS and 1/*f* noise measurements can provide complementary information about defects in linear bipolar devices.**

Index Terms**— Bipolar transistors, defects, DLTS, displacement damage, low-frequency noise.**

I. Introduction

Bipolar junction transistors (BJTs) are widely used in many electronic systems due to their high driving capability, linearity, and speed advantages [1], [2]. The reliability of BJTs in space systems and their radiation responses have been extensively studied since the 1950s [3]–[5]. Heavy ion-induced degradation has been studied via deep level transient spectroscopy (DLTS). Several defects that are important to the BJT radiation response have been identified [6]–[11]. In addition, Li *et al.* have employed DLTS measurements to investigate synergistic effects of ionization and displacement defects in *n-p-n* BJTs irradiated by heavy ions [12], [13].

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Low-frequency (LF) noise measurements can also provide insight into the density and energy distributions of defects in microelectronic devices and materials [14]–[16]. Numerous studies of as-processed and irradiated devices have shown that the LF noise is more strongly affected by defects at the interface of the oxide that overlies the emitter-base (EB) junction than by bulk defects within the junctions [17]–[24].

In this paper, we perform DLTS and LF noise measurements to evaluate the types of defects and resulting defect energy distributions before and after 17 MeV Si ion irradiation of 2N2222A *n-p-n* Si BJTs. DLTS measurements identify four prominent defect levels in the bulk Si that are introduced by irradiation in the base-collector junction of these transistors. Temperature-dependent 1/*f* noise measurements identify at least two defect levels, one of which appears to be similar to levels identified via DLTS, and the other that is likely associated with oxygen vacancies and hydrogen complexes in the interfacial oxide layer that overlies the EB junction. These results demonstrate that DLTS and LF noise methods provide complementary information about defects in linear bipolar devices.

II. Experimental Details

Devices under test (DUTs) were Central Semiconductor 2N2222A *n-p-n* Si BJTs, which is a general purpose, low power planar epitaxial transistor commonly used in space and defense systems. See Fig. 1(a) for a schematic diagram [25]. The base doping and collector doping of the DUT are ~3.4×10^{16} cm^{-3} and ~4×10^{14} cm^{-3}, respectively. 17 MeV Si ions are chosen to create end-of-range defects, mimicking neutron cluster damage primarily caused by silicon recoils [10], [26], [27]. SRIM simulation in Fig. 1(b) shows that the range of the 17-MeV Si ions in silicon is 6.44 μm, consistent with the collector depth. Ion irradiations were performed at the Ion Beam Laboratory at Sandia National Laboratories up to a fluence of $10^{10}/cm^2$. The beam was focused to a size somewhat larger than the transistor die (~0.5×0.5 mm^2). All device terminals were grounded during irradiation.

Defects at the base-collector depletion zone in the collector of these devices are most efficiently probed via DLTS measurements [7]–[11] because of the relatively low doping and large depletion width of the N-epi layer [11]. Thus, DLTS measurements were performed after ion irradiation with the base-emitter junction shorted using a filling pulse amplitude of 5 V, a quiescent reverse bias of −5 V, a 1 ms fill pulse, and 100 ms transient length. Changes in capacitance were measured during temperature scans from 60 K and 325 K and the measurements were analyzed using standard techniques [7], [8], [28].

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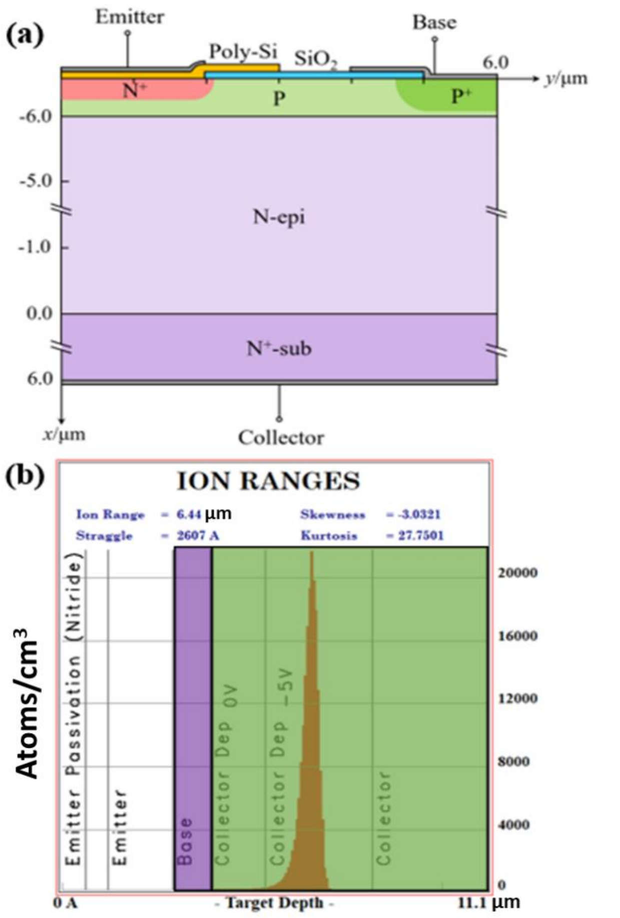

Fig. 1. (a) Schematic cross section of a 2N2222A *n-p-n* Si BJT. (After [25].) (b) The number of vacancies as a function of depth in *n-p-n* BJTs induced by a single 17 MeV Si ion impact (simulated by SRIM).

Forward Gummel characteristics of the samples were measured with a HP4156 semiconductor parameter analyzer before and after Si ion irradiation at fluences from 10^6/cm^2 to 10^{10}/cm^2 in a common-emitter configuration. The base-emitter junction bias V_{BE} of the samples was swept from 0 V to 1 V at V_{CE} = 1 V during measurement [29], [30]. Ten devices were tested from the same diffusion lot. To within ± 3% experimental uncertainty, as-processed devices exhibited identical *I-V* and *C-V* characteristics (not shown). Typical results are reported in this work.

LF noise measurements were performed as a function of base current and temperature with BJTs biased in a common-emitter configuration [19]. To measure the current noise of the BJT, a low-noise metal film resistor R_L (typically ~1 kΩ) was placed in series with the collector. The collector bias was chosen to operate the device in active mode. The noise signal of the voltage power spectral density S_{VC} from the collector biasing resistance R_L was amplified by a Stanford Research (SR) 560 low-noise amplifier and then measured with a SR 760 dynamic spectrum analyzer at a constant I_B at frequencies from 3 Hz to 390 Hz. Base current fluctuations S_{IB} lead to voltage noise S_{VC}; these were extracted via the relation $S_{IB} = \frac{S_{VC}}{R_L^2 \beta^2}$, where β is the current gain [17]–[23].

III. Experimental Results and Discussion

A. Electrical Characteristics

The room-temperature forward Gummel characteristics are shown in Figs. 2(a) and 2(b) before and after irradiation with different ion fluences. The base current I_B gradually increases with Si ion fluence and is more sensitive to the radiation damage than I_C [29], [30]. Si ions induce ionization and displacement damage in BJTs leading to an increase in carrier recombination and degradation in β [29]. The recombination current in the emitter-base junction varies as exp (V_{BE}/nV_T), where V_{BE} is the bias voltage across the emitter-base junction, n is the ideality factor and V_T is the thermal voltage [29], [30]. The ideality factor n for I_B increases with increasing fluence from 1.02 to 1.36 in Fig. 2(b). In BJTs, recombination in the neutral base exhibits an ideality factor n = 1; an ideality factor n = 2 is associated with recombination in the emitter-base depletion region [1], [29], [30]. Hence, for these devices the percentage of emitter-base depletion recombination current increases with ion exposure [29], [30], [31].

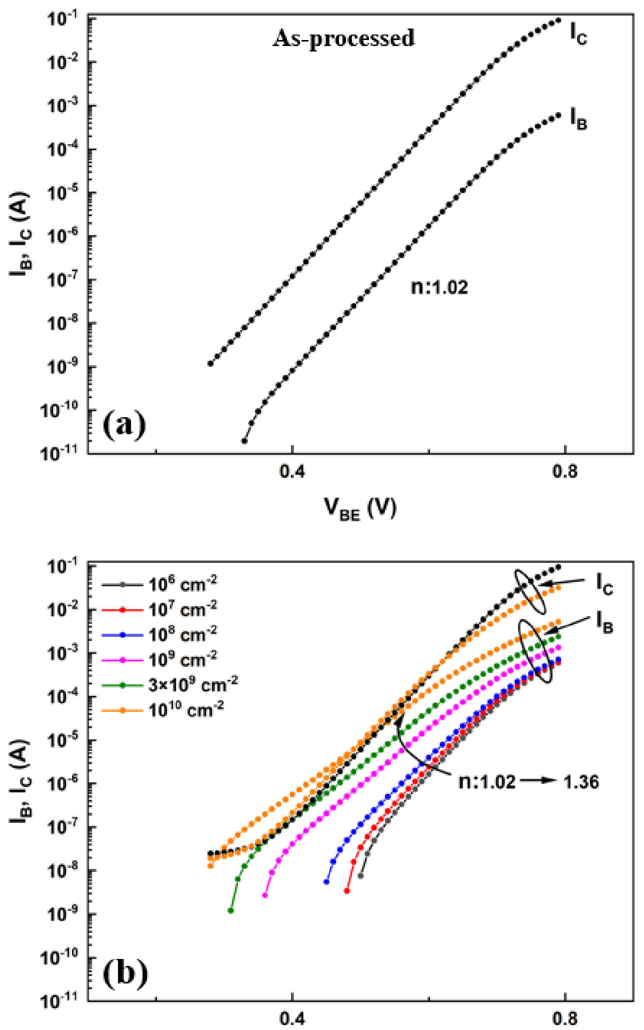

Fig. 2. Room-temperature forward Gummel plots for 2N2222A *n-p-n* Si BJTs at V_{CE} = 1 V (a) before and (b) after 17 MeV Si ion irradiation up to a fluence of 10^{10}/ cm^2. The extracted ideality factor n is shown in (b).

The change in the reciprocal of the gain variation ($\Delta(1/\beta)$) is defined as the value after irradiation minus the initial gain, $\Delta(1/\beta) = 1/\beta - 1/\beta_{\text{As-processed}}$. Fig. 3 shows $\Delta(1/\beta)$ at V_{BE} = 0.65 V as a function of fluence for 17 MeV Si ion irradiation of the *n-p-n* Si BJT devices. The values of $\Delta(1/\beta)$ increase linearly with ion fluence, and are suitably characterized by the Messenger–Spratt equation [10], [32]:

$$\Delta(1/\beta) = K\Phi. \quad (1)$$

Here, K is the damage factor and Φ is the incident particle fluence.

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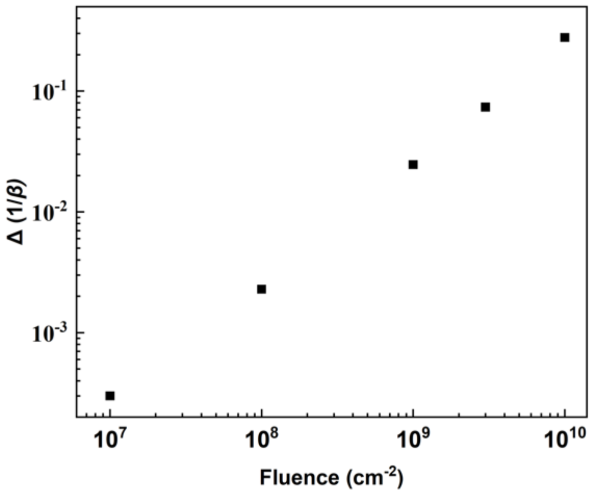

Fig. 3. Changes in the reciprocal of current gain ($\Delta(1/\beta)$) as a function of fluence for *n-p-n* Si BJTs irradicated by 17 MeV Si ions (V_{BE} = 0.65 V).

B. DLTS measurements

Fig. 4(a) shows DLTS spectra of the base-collector junction of the *n-p-n* Si BJT devices at a Si ion fluence of 10^9/cm^2 at four rate windows ranging from 4.3 ms to 43 ms. Four major peaks are observed in the spectra; the corresponding Arrhenius plots associated with these peaks are shown in Fig. 4(b). Vacancies, interstitials, and point defect/impurity complexes lead to various defect levels in the Si band gap, resulting in the degradation of current gain of BJTs [26], [27]. Three of four peaks in Fig. 4 (a) correspond to classic defects in Si [7], [10], [33]–[36]. The vacancy-oxygen (VO) trap produces a level at ~0.17 eV below E_C and a DLTS peak at ~90 K [6]–[10], [33], [34], [36]. The shallow divacancy in Si (V_2 (=/−)) has a level at ~0.24 eV below E_C corresponding to ~140 K [7], [33]-[36]. The peak at ~230 K (E_C − 0.43 eV) is composed of the vacancy phosphorous (VP), the divacancy (V_2 (−/0)) and other complex defects such as E5 centers [7]-[10], [33]–[36]. The defect level at ~280 K (~0.53 eV) appears to be unique to these Central Semiconductor *n-p-n* Si BJTs; this trap evidently is purposefully created to reduce carrier lifetimes in the as-processed devices.

Fig. 4(c) shows DLTS spectra at the rate window of 4.3 ms as a function of fluence. In the DLTS spectra, the peak height is proportional to the trap concentration [28]. Increasing fluence yields higher defect amplitudes in the DLTS spectra at ~230 K. Thus, deeper levels, such as V_2 (−/0) and E5 centers are the critical defects that degrade the current gain in these devices [8],[9]. In contrast, a decrease in the peak at ~280 K is observed, suggesting passivation of the defects at the ~0.53 eV energy level in the as-processed devices via ion exposure. The densities of VO and V_2 (=/−) increase at fluences up to 10^9/cm^2 and then decrease at higher fluences. This is because the defects at ~230 K cause band bending and those shallow levels are no longer filled at higher ion fluences [7], [9].

C. Low-frequency noise measurements

Fig. 5 shows extracted base noise current power spectra density S_{IB} normalized by I_B^2 with I_B varying from 1 μA to 16 μA for (a) an as-processed device and (b) an irradiated device at the Si ion fluence of 10^{10}/cm^2. The noise magnitude increases significantly after irradiation. The spectra exhibit $1/f^{\alpha}$ frequency dependences for most frequencies and values of I_B, and are generally similar in shape to those

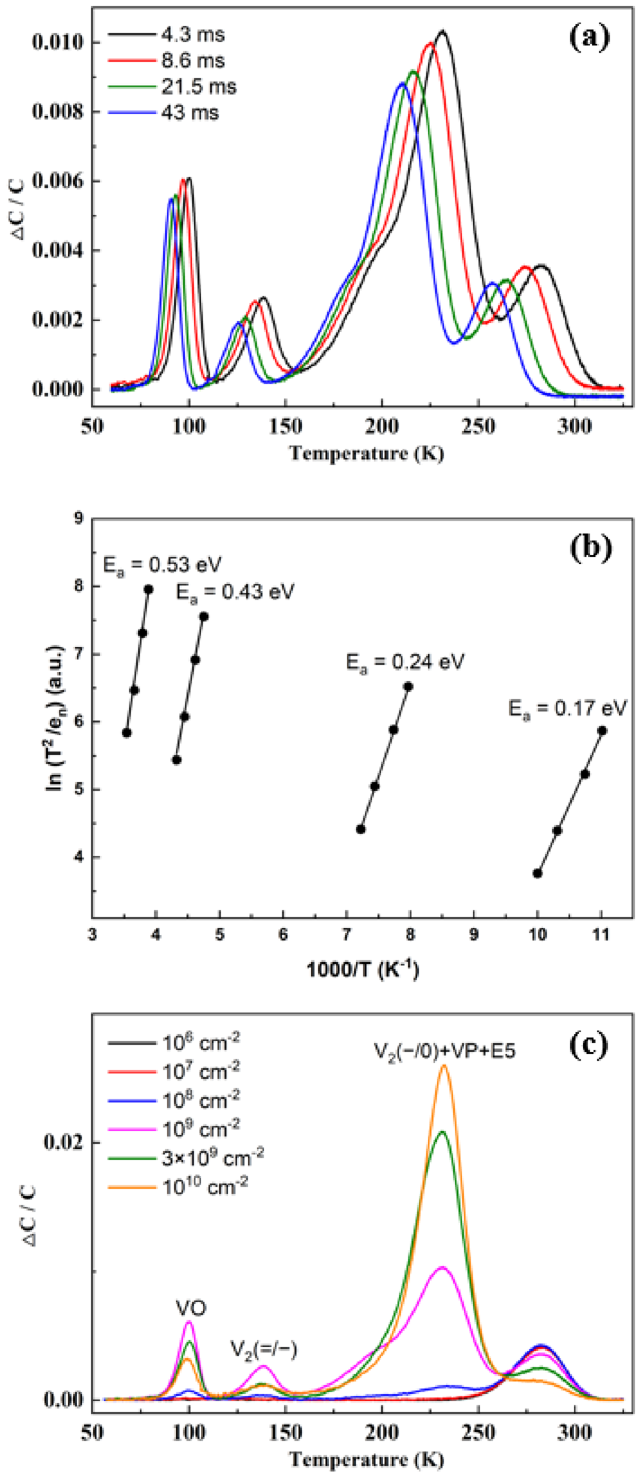

Fig. 4. (a) Normalized DLTS spectra at different rate windows of the base-collector junction in the *n-p-n* Si BJT devices at a Si ion fluence of 10^9/cm^2 and (b) the Arrhenius plots corresponding to the four DLTS peaks. (c) Normalized DLTS spectra at the rate window of 4.3 ms vs. fluence for Si ion irradiations up to a fluence of 10^{10}/cm^2.

observed in other Si BJTs [17]–[23]. The fluence dependence of S_{IB} at 10 Hz and I_B = 2 μA is shown in Fig. 5(c). The noise level increases to fluences up to 10^9/cm^2 and then decreases slightly at higher fluences. This trend is similar to that of the densities of VO and V2 defects (=/−) in DLTS, for example.

Temperature-dependent measurements of low-frequency noise can provide significant insight into the effective defect-energy distributions for the processes responsible for the current fluctuations in semiconductor devices. Dutta and Horn have shown that if the noise is caused by a random

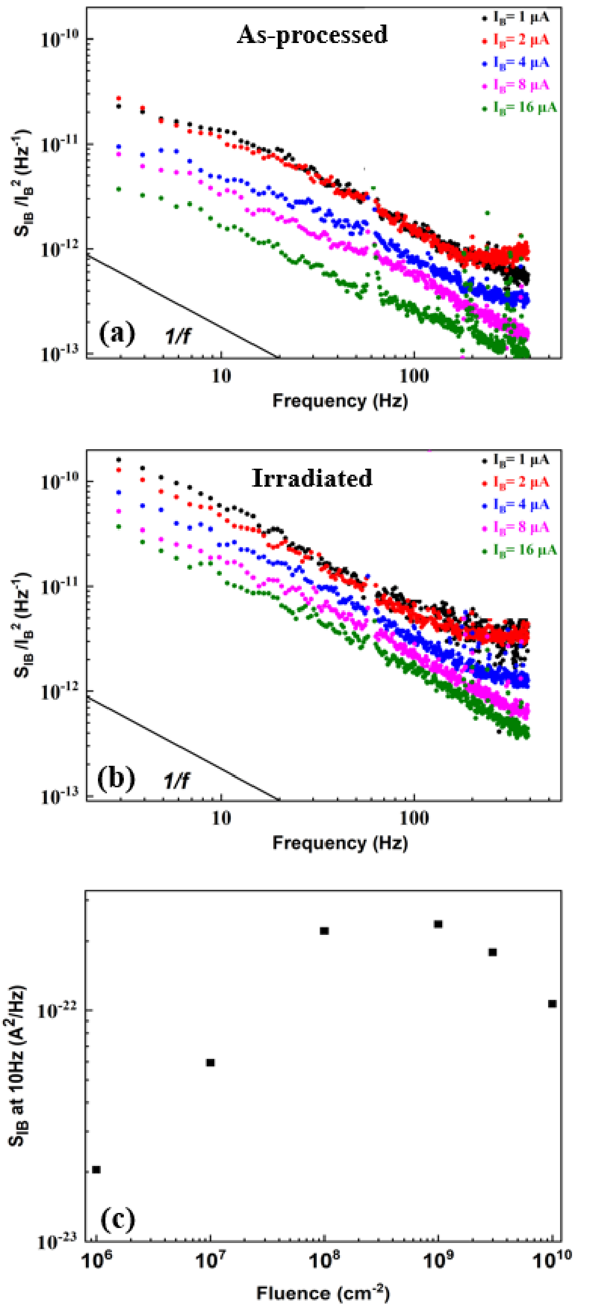

Fig. 5. Normalized current-noise power spectral density, S_{IB}/I_B^2, vs. f at various I_B for *n-p-n* Si BJTs (a) as-processed, and (b) post-irradiation. (c) Effects of irradiation on the fluence dependence of the noise at 10 Hz with $I_B = 2$ µA. Devices were operated in the active region. Unwanted spikes from 60-Hz pickup and harmonics are removed.

thermally-activated process that exhibits a broad distribution of energies $D(E_0)$ relative to kT, where k is the Boltzmann constant and T is the temperature, the frequency exponent shows a temperature dependence described to first order by [15], [16], [37], [38]:

$$\alpha(\omega, T) = 1 - \frac{1}{\ln(\omega\tau_0)}\left(\frac{\partial \ln S_V(T)}{\partial \ln T} - 1\right). \quad (2)$$

Here S_V is the excess voltage–noise power spectral density after the thermal noise is subtracted and $\alpha = \partial \ln S_V / \partial \ln f$, $\omega = 2\pi f$, and τ_0 is the characteristic time of the process leading to the noise. The value of τ_0 is taken to be ~ 1.8×10^{-15} s based on experimental studies of the charge trapping and emission kinetics of oxide and border traps near the Si/SiO_2 interface [16], [39]. From measurements of the temperature dependence of S_V, we estimate the effective defect-energy distributions $D(E_0)$ [15], [16] via

$$D(E_0) \propto \frac{\omega}{kT} S_V(\omega, T). \quad (3)$$

Here, the defect energy E_0 is given by [15], [16], [39]:

$$E_0 \approx -kT \ln(\omega\tau_0) \quad (4)$$

If the noise is due to thermally activated processes with two energy levels, E_0 is the barrier the system must overcome to move between two configurational states [15]–[17]. We note that Dutta-Horn analysis has been shown to be applicable to noise due to both carrier-number and carrier-mobility fluctuations [16], [37]–[41]. Fluctuations in both carrier number and mobility likely occur in these devices [17]–[24].

Temperature-dependent *1/f* noise measurements were performed from 80 K to 380 K in steps of 10 K. During noise measurements, the device was biased at I_B = 2 µA and operated in the active mode. In the literature, it is unusual to find temperature-dependent noise measurements for linear bipolar transistors. Understanding their capabilities and potential limitations is, therefore, important not only to this study but to future work on defect characterization.

Fig. 6 shows noise spectra in the 2N2222A *n-p-n* Si BJTs at selected temperatures before and after Si ion irradiation. For the as-processed device, $1/f$ noise dominates over S_{IB} for the lower-frequency range, $f < 100$ Hz. S_{IB} is of the "generic" $1/f^{\alpha}$ type in irradiated devices [15], [16]; the extracted frequency exponent α varies between 0.9 and 1.1. As shown in Figs. 6(a) and (b), the noise magnitudes are much higher for the irradiated devices than the as-processed devices owing to ion-induced defect creation. The upturn in noise at frequencies above ~ 100 Hz is attributed to diffusion noise caused by fluctuations in carrier density and mobility in the base [17]–[23]. This noise is significant to the

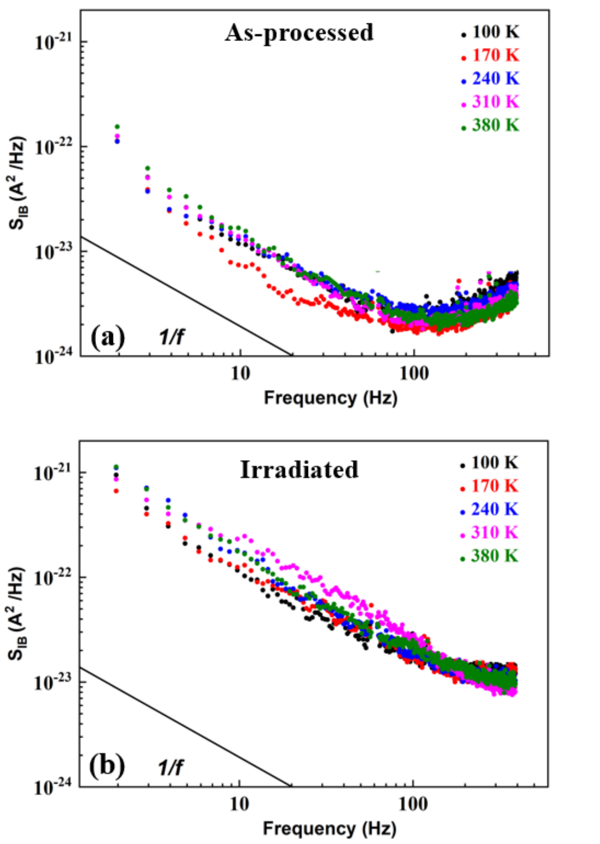

Fig. 6. Current-noise power spectral density, S_{IB}, vs. f at various temperatures for *n-p-n* Si BJTs (a) before and (b) after a fluence of 10^{10}/ cm^2 17 MeV Si ion irradiation. Unwanted spikes from 60-Hz pickup and harmonics are removed.

performance and reliability of linear *n-p-n* transistors but does not scale with fluence or effective defect density in the same way as the lower-frequency noise which behaves more similarly to the noise in MOS devices [15], [16]. This suggests that the noise below ~100 Hz may have a surface origin, e.g., resulting from fluctuations in the carrier density due to charge trapping and emission at the upper surface between the base-emitter junction and the base oxide (Fig. 1) [15], [16], [29], [39]–[41].

Fig. 7 shows the normalized low-frequency noise $S_{IB}*f/T$ as a function of temperature at f = 20 Hz and I_B = 2 μA for the devices before and after Si ion irradiation. After irradiation, the noise magnitude increases significantly with increasing fluence. The energy scales on the upper *x*-axis in Fig. 7 are derived from the Dutta–Horn model via Eq. (4). These scales are sensitive to the chosen value of τ_0 in (2) and (4). Due to the logarithms in these expressions the energy scale only changes by 10-15 % when τ_0 is varied by several orders of magnitude [15], [40].

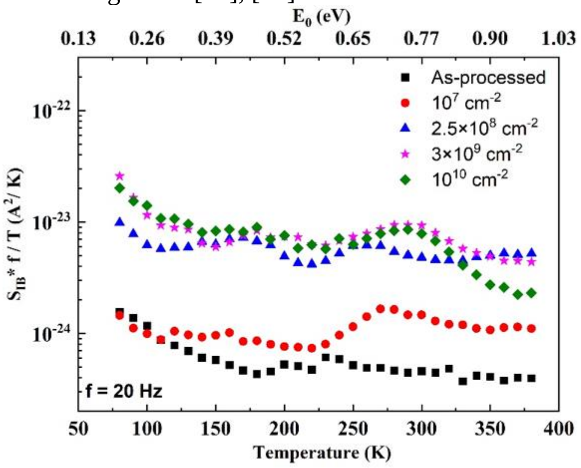

Fig. 7. Normalized 1/*f* noise for *n-p-n* Si BJTs as a function of temperature from 80 K to 380 K at f = 20 Hz and I_B = 2 μA.

The applicability and validity of the Dutta-Horn model of 1/*f* noise to the devices of this work is demonstrated by the results of Fig. 8. The measured values of the frequency exponent α from noise data for the devices before and after a fluence of 10^{10}/cm^2 Si irradiation agree well with Eq. (4) [15]. The applicability of the Dutta-Horn analysis confirms that the noise in Si BJTs is caused by thermally activated processes. The energy scale in Fig. 7 differs from that in Fig. 4 by 15-20% due to the small differences in the rate windows, the uncertainties in the values of τ_o, and the differences in the approximations made in the treatments of the Arrhenius prefactors in the DLTS analysis [21] and Dutta-Horn theory [15]. Similar offsets can be observed between the energy scales for 1/*f* noise and thermally stimulated current measurements [39]. The resulting differences are within the combined uncertainties of the respective methods [15], [28], [39]. In Section III.D, we focus primarily on comparisons between the temperatures of observed peaks in Figs. 4 and 7 to avoid uncertainties in the respective energy scales.

After irradiation of the devices to a fluence of 10^7/cm^2, a noise peak is observed at ~270 K. After further irradiation of the devices to 10^{10}/cm^2, broad peaks centered at ~180 K and ~290 K are observed. In MOS devices, these border traps leading to 1/*f* noise are often associated with a distribution of defects, including oxygen vacancies and hydrogen complexes [16], [39], [40]. Recently, contributions to 1/*f* noise that result from the sequential, reversible activation and passivation of interface traps have also been identified [41]. Such defects may well contribute to the noise in these devices if located at the interface of the base oxide and the base-emitter junction, for example [29]. However, bulk defects are also likely to contribute to the observed noise in linear bipolar transistors [17]–[23], [41].

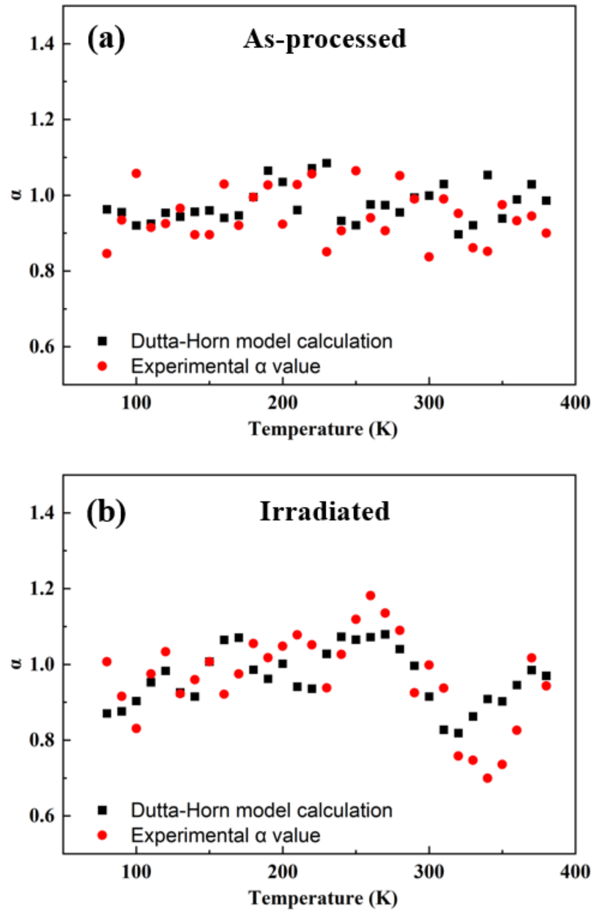

Fig. 8. Experimental and calculated (from Eq. (4)) frequency exponents α for device (a) before and (b) after a fluence of 10^{10}/cm^2 Si irradiation with S_{IB} at 20 Hz.

D. Comparison of DLTS and 1/f noise

While DLTS primarily senses defects at the base-collector junction of the BJT and the 1/*f* noise appears to be more sensitive to defects at the base-emitter junction with the base oxide (Fig. 1), it is still interesting to see how the effective defect energy distributions may compare for the two techniques. As in earlier comparisons of 1/*f* noise and thermally stimulated current measurements in MOS devices [39], these results illustrate how each method may reinforce and/or complement results of the other.

Comparing Figs. 4 and 7, VO defects are clearly visible at ~100 K in the DLTS spectrum, and there is an upturn in noise magnitude at temperatures below 100 K that could be associated with the same defect. However, neutral hydrogen diffusion occurs with similar energy levels [42], [43], so hydrogen-induced trap activation and passivation may also play a role in the 1/*f* noise at these temperatures [41]. The small V2 peak at ~140 K in the DLTS spectrum in Fig. 4 is matched by a small upturn in noise magnitude in Fig. 7 at similar temperatures. However, H_2 diffusion and reactions with charged defects also occur with similar activation energies near Si/SiO_2 interfaces [44]–[46], providing an alternative explanation for the noise results [47], [48].

The large peak at ~240 K in DLTS in Fig. 4 is entirely missing from the 1/*f* noise measurements. Hence, the defects in this case are clearly affecting primarily the base/collector interface upon which the DLTS measurements are focused [6]–[11]. The absence of this peak in the noise measurements shows its insensitivity to defects at this junction for these devices. Interestingly, at 280 K both DLTS and 1/*f* noise show prominent defects. However, inferred concentrations of these decrease with fluence during DLTS measurements and increase with fluence during noise measurements, suggesting that the two defects most likely differ in microstructure and/or location. The peak in noise measurements at these energies has been associated with H^+ motion and reactions at or near Si/SiO_2 interfaces [49]–[52].

Taken together, the differences in the temperature and fluence dependences of the DLTS and low-frequency noise defect energy distributions in Figs. 4 and 7 show that each method is indeed primarily probing a different region of the linear bipolar transistor. Hence, the two methods provide complementary and not duplicative information about defects in the transistor structure. For DLTS, primarily bulk defects are observed at the base-collector junction. For low-frequency noise, traps at the junction of the base, emitter, and base oxide evidently play a more significant role. We note that this result contrasts with recent DLTS and low-frequency noise measurements in GaN-based HEMTs in which similar defects are observed via temperature-dependent noise and DLTS measurements [53]–[59]. The similarity of the results in these cases is most likely because defects and impurities in the GaN buffer layer (e.g., nitrogen vacancies and substitutional iron, Fe_{Ga}) are sensed in both noise and DLTS measurements of GaN-based HEMTs [53]–[59]. One should not expect such similarity to always occur in other devices, e.g., these linear bipolar transistors.

IV. Summary and Conclusions

DLTS and low-frequency 1/*f* noise measurements are compared for *n-p-n* Si BJTs as a function of fluence for 17-MeV Si ion irradiation. The base current I_B increases with increasing fluence, and thus the gain degrades. DLTS spectra show that the oxygen vacancy (VO), the shallow divacancy (V2 (=/−)), and a composition of the vacancy phosphorous (VP), divacancy (V2 (−/0)) and other complexes such as E5 centers are generated in the base-collector junction of the transistor after irradiation. The underlying mechanisms for the decrease in amplitude of the unique peak at ~280 K with increasing fluence remain under investigation.

The 1/*f* noise magnitude for these devices increases significantly after ion irradiation. A combination of contributions from oxygen vacancies and hydrogen complexes in the oxide that overlies the base-emitter junction is inferred from measurements of the temperature dependence of the noise below 100 Hz, although contributions from bulk defects is also possible. The diffusion noise at higher frequencies is dominated by fluctuations in carrier number and mobility for transiting carriers in the base. A detailed comparison of the effective energy distributions and magnitudes of the defects identified via DLTS and 1/*f* noise measurements show that these techniques provide complementary information about the performance, fluctuation phenomena, and radiation response of linear bipolar transistors. This contrasts with recent work that shows that DLTS and LF noise measurements sense similar defects in GaN-based HEMTs, for example, reinforcing the benefits of using multiple techniques to characterize defects in semiconductor materials and devices.

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