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Evidence against existing x-ray-energy response theories for silicon-surface-barrier semiconductor detectors

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The detailed x-ray-energy response of silicon-surface-barrier (SSB) semiconductor detectors is investigated using synchrotron radiation from a 2.5-GeV positron storage ring. These data are found to be contrary to existing theoretical predictions for the response based on (i) the silicon-depletion-layer thickness (the commonly held belief described in textbooks), and (ii) the silicon-wafer thickness (a recent proposal). This finding affects not only previously published conclusions on analyzed plasma-electron temperatures using these existing SSB theories but also the resultant discussions on plasma behavior reported from various plasma devices. Also, this information is of importance for ongoing and future analyses of SSB data so as to avoid making further misinterpretations from the analyzed results. A possible physical interpretation for these unexpected SSB response data is discussed using thermal charge-diffusion effects in the SSB substrate. These discussions provide the physics bases to solve this unexpected problem for the actual SSB response; that is, where the actual SSB-sensitive layer is, and what the physical mechanism for this SSB response is.

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Silicon-diode detectors are widely utilized for the plasma-electron diagnostics. An x-ray tomographic-reconstruction technique [1–10] is one of the most important and commonly employed diagnostic methods, since observations of spatially resolved plasma-electron temperatures T_e give useful information on detailed electron behavior [1–12].

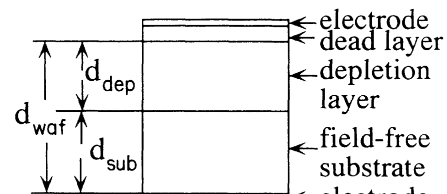
However, recent papers [13,14] reported an unexpected x-ray-energy response of partially depleted silicon-surface-barrier (SSB) diode detectors in a current-mode operation using two x-ray energies from isotopes; these papers claim that the SSB response is determined from its silicon-wafer thickness [13,14], and is contrary to the commonly held belief that the x-ray-sensitive region is the depletion layer.

This difference requires serious corrections for previously estimated values of T_e and the resultant physics discussions using them; in particular, for high-energy x rays penetrating through the depletion layer, significant corrections for the estimated values of T_e are necessary. After these important reports [13,14], researchers have been left in serious confusion. In this paper, therefore, the detailed x-ray-energy response of SSB detectors is investigated to reconstruct the principles for the SSB data analyses.

The experiments have been carried out in the following: A 2.5-GeV positron storage ring having a mean diameter of 60 m at the Photon Factory of the National Laboratory for High Energy Physics provides intense synchrotron radiation [10,15–20]; the energy is monochromatized and automatically changed using a computer-controlled double-crystal [Si(111)] monochromator [14,15] with an energy resolution of a few eV. The purity of the energy is monitored using an NaI(Tl) detector [7]. X rays ranging from 5 to 20 keV are incident in the shape of 2×5 mm^2 on three SSB detector surfaces with 19.5 mm in diameter (Fig. 1). The x-ray flux is monitored by ionization chambers using nitrogen or argon gas [15,16].

In Fig. 1 are shown a schematic view and the parameters of the SSB detectors. X-ray absorption in the electrode or the dead layer (Fig. 1) is negligible for our energy range. The accuracy of the tabulated values was confirmed using pulse-height analyses [21].

In Fig. 2(a), the data on the ratio of the detector efficiency of the "RT" detector (see Fig. 1) for a unit incident x-ray flux divided by its energy ("RT" denotes R-series Tennelec detector), η_{SSB}/E [19], are plotted as dots. The solid curve stands for the calculated value for the conventional theory; that is, η_{SSB} is determined from the total amount of x ray created charge in the depletion-layer thickness d_{dep} alone. The dashed curve is calculated from the recent prediction reported in Refs. [13] and [14]; that



SSB detectors	d_{dep}	d_{waf}
RT	218μm	360μm
RO	180μm	510μm
BO	215μm	215μm

FIG. 1. Schematic view of a silicon surface-barrier (SSB) semiconductor detector. The existence of a field-free substrate region characterizes a partially depleted SSB detector. Also, the parameters of three SSB detectors employed are tabulated.

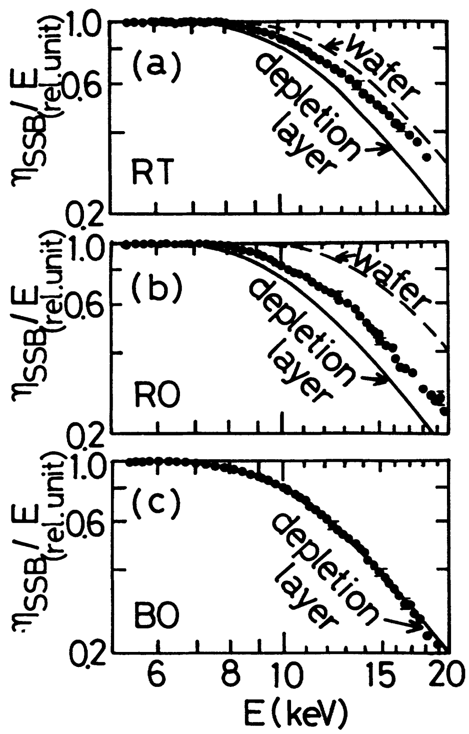


FIG. 2. The energy responses of three SSB detectors tabulated in Fig. 1 for a unit incident x-ray flux divided by the x-ray energy, η_{SSB}/E. Each solid curve in (a)–(c) stands for the calculated value from the conventional theory using the depletion-layer thickness alone as the x-ray-sensitive layer, while each dashed curve in (a) and (b) indicates the calculated value using the corresponding silicon-wafer thickness as the x-ray-sensitive region. Data obtained in our experiments are plotted as dots in each figure.

is, η_{SSB} is determined from the total charge created all through the wafer thickness d_{waf}. A clear discrepancy between the data and each theoretical curve is found; the reproducibility is carefully checked using data obtained from four machine times in these three years. This feature is also seen in Fig. 2(b); here, the data of the "RO" detector ("RO" denotes R-series Ortec detector) clearly deviate from the dashed curve calculated using its thicker wafer thickness. On the other hand, in Fig. 2(c) are shown the data of the "BO" detector ("BO" denotes B-series Ortec detector) having no substrate region. The data agree well with the conventional theoretical prediction using d_{dep}.

The comparison of these three data sets clearly indicates the applicable limit of existing theories for all types of SSB detectors. Furthermore, these data imply an essential role of the substrate region in the SSB response. In view of the importance of the field-free region, the papers in Refs. [13] and [14] are essential although they proposed the importance of d_{waf} for η_{SSB}.

A possible explanation covering over the above-mentioned experimental evidence for SSB detector responses is constructed using the following physical interpretations: The conventional theory for the SSB response using the depletion-layer thickness is still valid for fully depleted SSB detectors (having no field-free substrate region) as is found from the data in Fig. 2(c). However, for partially depleted SSB detectors (having a field-free substrate region), further effects should be added to the above conventional theory for interpreting the SSB data in Figs. 2(a) and 2(b). From the similar SSB responses in Figs. 2(a) and 2(b), this additional effect is not simply attributed to the substrate thickness (or the wafer thickness), since the wafer thicknesses of these SSB detectors are significantly different. A possible physical interpretation for these SSB responses is made using thermally diffusing charge created in the substrate by x rays penetrating through the depletion layer. If whole charge created in the substrate by the absorption of the penetrating x rays is collected and contributes to the SSB signal, then the signal should be larger for the SSB having a thicker wafer. However, the data do not support this, although the existence of important roles of the substrate region in this SSB response data is actually anticipated from the data comparison in Fig. 2. This problem is solved by introducing the charge-recombination effect in the SSB substrate region, where the created charge diffuses slowly at the thermal velocity. The recombination occurs at the same rate for the same kind of substrate materials; the recombination rate depends on the concentration of impurity ions (recombination centers) in the silicon substrate. The thermal-diffusion length L (the e-folding length [the length where a certain signal intensity becomes $\exp(-1)$] of the thermally diffusing charge) ranging 50–100 μm provides the following explanation of nearly the same η_{SSB} curves for the two detectors having different d_{waf}: The thickness of each substrate of the RT and RO detectors is sufficiently larger than L; thereby, diffusing charges created at locations deeper than L in the substrates recombine along the diffusion paths before reaching the depletion layer where charges are swept quickly to an electrode along electric fields.

In Fig. 3, the data from both RT and RO detectors have been fitted using this effect. The theoretical formula for the SSB response is obtained after lengthy calculations using a diffusion equation as qualitatively discussed above (for more detailed quantitative treatments to solve the equation, see Ref. [22]). The formula is described by the combination of the contributions from the depletion layer [the first two terms on the right-hand side of Eq. (1)] and the substrate region (the remainder term).

$$\frac{\eta_{SSB}}{E} \propto [1-\exp(-\mu\rho d_{dep})] + \tfrac{1}{2}\exp(-\mu\rho d_{dep}) \times \left[\frac{\mu\rho L}{\mu\rho L+1} + \ln(1+\mu\rho L)\right], \quad (1)$$

where μ and ρ denote the silicon mass-absorption coefficient and the mass density, respectively. In Fig. 3, as we expected from the above discussions, the calculated curve using $L=75$ μm from Eq. (1) lies between the solid curve (the depletion-layer contribution alone being taken into account) and the dashed curve (whole wafer thickness being utilized as the SSB sensitive region).

The purpose of the present paper is a quick report of our experimental results of the SSB response; however, the good agreement between the data and the theoretical

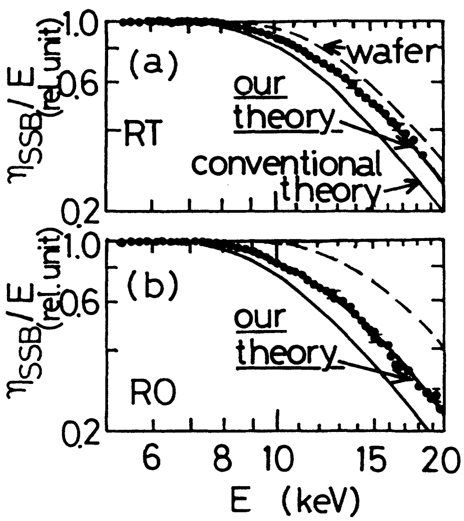


FIG. 3. The experimental data [see Figs. 2(a) and 2(b)] are compared with the prediction from our new theory on the energy response of SSB detectors [see Eq. (1)]. The data-fitting curves are calculated using the combination of the conventional depletion-layer contribution and of the charge contribution diffusing from the field-free substrate region to the depletion layer within the thermal charge-diffusion length L of 75 μm. It is noteworthy that both data in (a) (the RT detector having $d_{\rm sub}=142$ μm) and (b) (the RO detector having $d_{\rm sub}=330$ μm) are fitted using $L\approx 75$ μm: If the value of L ranged between 142 and 330 μm, then a larger contribution of diffusing charge for the RO detector having $d_{\rm sub}>142$ μm would be anticipated compared with the diffusion contribution for the RT detector. Similar response data for both detectors consistently support the range of $L\approx 75$ μm, which is sufficiently less than 142 μm.

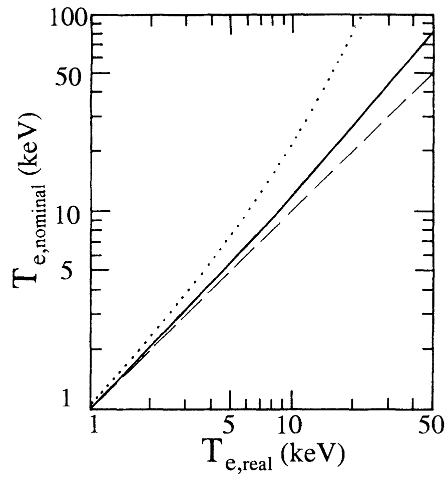


FIG. 4. An example of the applications of the actual response of the RT detector: Actual plasma-electron temperatures $T_{e,\rm real}$ reduced from x-ray bremsstrahlung emission (see Refs. [2] and [3]) using the SSB calibration data [or from Eq. (1)] are compared with those using the commonly utilized conventional theory on the SSB sensitivity $T_{e,\rm nominal}$ (the solid curve). The overestimation of electron temperatures using the conventional theory arises from the underestimation of the SSB response as seen in Fig. 3 (thereby, the overcompensation for the temperature estimation). On the curve, the same x-ray-emission level is calculated using the above different SSB response theories (or the SSB calibration data). The dotted curve is the result from not only the use of the conventional theory but also the misusage of the nominal catalogue value (100 μm) of the depletion-layer thickness for the RT detector.

formula in Eq. (1) provides an important suggestion for the existence of an additional effect to the conventional SSB response theory using the depletion-layer sensitivity alone. Naturally, the BO response is fitted using the conventional theory without the thermal-diffusion effect from the substrate region; this is generalized in our theory as a special case without the substrate contribution.

In Fig. 4, as one of the application examples of the above discussions, a remarkable effect from widely employed but incorrectly used conventional theory on $\eta_{\rm SSB}$ for partially depleted SSB detectors is clearly illustrated: When the conventional theory using $d_{\rm dep}$ alone is utilized, plasma-electron temperatures are overestimated by more than 40% at $T_e=35$ keV for instance; here, we assume the Maxwellian electron-velocity distribution function so as to calculate x-ray bremsstrahlung emission from the electrons (see Refs. [2] and [3]), and we employ Eq. (1) for the actual SSB response calculation. This remark shown in Fig. 4 is enhanced if one remembers common usages of p-i-n diodes widely utilized in underbiased operations for avoiding breakdown; this leads to similar substrate-region formation, and results in similar serious misinterpretations for electron-temperature analyses. Furthermore, it should be carefully noted that the thickness of the depletion layer given by manufacturers' catalogs is merely a nominal value although several papers employed such a value as an actual depletion-layer thickness. (For our RT and RO detectors, each nominal depletion-layer thickness is only 100 μm). The dotted curve in Fig. 4 calculated by using such a nominal value for the ordinate provides a further drastic overestimation for electron temperatures as well as its resultant misinterpretations for plasma physics. For the actual temperature of 20 keV, for instance, the miscalculation of a 80-keV temperature is resulted from the use of this catalog value for the depletion-layer thickness.

Finally, it is noted that the thermal charge-diffusion effect in the field-free substrate region is expected to exist for various types of p-n junction based silicon detectors including photodiodes, the above described p-i-n diode detectors in underbiased operations and widely utilized charge-coupled devices. Therefore, in addition to the conventional depletion-layer sensitivity, the inclusion of this diffusion effect might provide a generalized response theory covering over all these semiconductor-detector responses, although these detectors are at present classified as different types of semiconductor detectors.

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