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X-Ray Response of Silicon Surface Barrier Diodes at 8 and 17.5 keV: Evidence that the X-Ray Sensitive Depth is not Generally the Depletion Depth

Kevin W. Wenzel, Richard D. Petrasso

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Plasma Fusion Center

Massachusetts Institute of Technology

Cambridge, MA 02139

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The absolute X-ray response of 18 EG&G Ortec partially depleted silicon surface barrier diodes (SBDs) has been measured at 8 and 17.5 keV. In addition we have examined the X-ray response of 4 Tennelec and 2 United Detector Technology partially depleted SBDs. The variation in response to 8 keV X rays, for which the optical depth is about 5, is comparatively slight ($\lesssim 12\%$). The variation in response to 17.5 keV X rays, for which the optical depth is only ~ 0.7, is comparatively large ($\sim 100\%$). These variations are mainly attributable to differences in the SBD physical thicknesses, and thus to differences in optical depth. At both 8 and 17.5 keV the diodes respond linearly to large variations in incident flux (over 3 orders of magnitude). This linearity, and the diode X-ray response in general, is insensitive to large changes in the detector bias voltage; thus the depletion depth, proportional to the square root of the bias voltage, does not play a critical role in determing the X-ray sensitive depth. It is important to emphasize that this finding is contrary to the commonly held belief that the X-ray sensitive depth is equivalent to the depletion depth. In addition this result has a direct bearing on both SBD and PIN detectors intended for fully depleted operation, but used in an underbiased mode such that they are actually partially depleted. We conclude that SBDs have attractive features for quantitatively measuring X radiation from high intensity sources for which $h\nu \gtrsim 10$ keV.

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Introduction

Surface barrier detectors (SBDs), though widely used for detecting charged[1-5] and neutral[6,7] particles, have also been extensively employed for detecting and imaging high intensity X emissions from laboratory plasmas,[8-11] especially tokamak plasmas.[12-27] Table I lists several representative experiments where SBDs (and PIN diodes, also a widely used junction-based detector) have been used for detecting X rays generated in plasma devices. SBDs are especially well-suited for imaging tokamak plasmas for three reasons: first, the detector X-ray sensitivity is quite flat between 1 and 8 keV; second, the core electron temperature in tokamaks often ranges between 1 and several keV, and as a consequence the X emissions fall mainly in this range; and finally, X-ray emission levels from tokamaks are of sufficient intensity that surface barrier detectors can be conveniently used as photovoltaic detectors[37] in the current mode.

SBD calibration measurements have previously concentrated largely on the energy range between 0.3 and 8 keV.[38,15,8] In this paper we describe an improvement of these measurements at 8 keV and an extension to 17.5 keV, from which the high energy response of the detectors can be determined. This is an important issue if such detectors are to be used to accurately quantify high intensity X-ray sources with photon energies approaching and exceeding 10 keV. For example, SBDs and PINs are currently used for imaging high temperature tokamak plasmas for which $T_e \gtrsim 5$ keV,[26,33-35] and thus a significant fraction of the X emission is at or above 10 keV. In addition the high energy response becomes critically important in this imaging application if spatially and temporally resolved plasma thermometry[16,24,26] is attempted on high temperature plasmas.

To address this issue, this paper must necessarily discuss what constitutes the X-ray sensitive depth in a partially depleted SBD. For charged particle detection it is the depletion layer depth, proportional to the square root of the bias voltage, that determines

the sensitive depth.[2,39] In contrast our measurements at 17.5 keV, for which the detectors are not optically thick, strongly indicate that it is predominantly the physical thickness of the SBD that determines the X-ray sensitive region. (The optical thickness is defined as $\mu \rho t$ where μ is the mass absorption coefficient, ρ is the density, and t is the thickness of the silicon.) This is at least superficially surprising since outside the depletion layer there is ostensibly no electric field to sweep out charge carriers generated by the X rays. In addition one might expect the X-ray and β-particle responses of SBDs to be similar, because the X-ray attenuation, dominated by the photoelectric effect below ~30 keV and the Compton effect above that, results in an ionizing electron that is effectively a low energy β-particle, albeit one that has been created well inside the detector. Confusion has therefore understandably prevailed over this issue to the present, and we believe many workers have erroneously assumed that the depletion depth constitutes the X-ray sensitive depth.[8,26]

Indeed it would be extremely important if the X-ray sensitive depth were the depletion depth and could be trivially set by adjusting the bias voltage. Then, for example, plasma X-ray thermometry[16,24,26] could be much more simply, accurately and quickly accomplished by modulating the bias voltage. In fact it was with this in mind that Reference 15 searched for, but failed to find, a bias-dependent effect with 8 keV X rays. One of the major aims of the present paper was to search for a bias-dependent effect which should clearly manifest itself at higher X-ray energies. This failing, it was our aim to test whether the detector thickness was of central importance, as was suggested early on.[40]

It is important to note that the question of X-ray sensitive depth in an SBD is also valid for diodes intended for fully depleted[41] operation. If such diodes are run with a sufficiently low bias voltage, they are in actuality partially depleted. To avoid confusion, we refer to SBDs capable of operation in the fully depleted mode as "fully depleted". (Of course there is no distinction between the depletion depth and the physical thickness of an

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SBD that is actually operated in a fully depleted mode.) In addition, the problem of the X-ray sensitive depth also applies to PIN diodes, another photovoltaic diode characterized by a bias-dependent depletion depth as well as partially and fully depleted operation.

The paper is divided as follows. In Section I we describe the SBDs, X-ray source, calibration spectra and circuitry. Section II presents data on the uniformity and linearity of detector signals with X-ray intensity, the invariance of the SBD signal to large changes in detector bias voltage, and the absolute calibrations of 18 Ortec SBDs. We further discuss the issue of spectral purity and its verification. In addition we compare the responses of a small sample of surface barrier diodes from Tennelec and United Detector Technology. In general all partially depleted surface barrier diodes acted very similarly regardless of manufacturer. In Section III we summarize the most important findings of these measurements and briefly discuss the suitability of using SBDs for measuring the X emissions from high intensity sources for which $h\nu \gtrsim 10$ keV.

Ia. Silicon Barrier Diodes

General descriptions of SBDs are contained in References 39, 42 and 43. These diodes consist of a metal-semiconductor interface forming a rectifying junction such that a reverse bias voltage generates an electric field, which in turn causes a region depleted of free charge carriers (the depletion depth, which has a thickness proportional to the square root of the bias voltage).

The particular SBDs used here were 18 EG&G Ortec ruggedized model BR-017-050-100 partially depleted diodes ranging in age from a few months to over 10 years (Table II). Eleven of these SBDs are the same diodes used for numerous imaging studies of the X emissions from the Alcator-A[16] and Alcator-C[21] tokamaks at MIT, and, of particular importance here, for earlier absolute X-ray response measurements.[15] All 18 of these detectors have 1500 Å of aluminum deposited on the front surface of a silicon wafer that

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ranges in nominal thickness from 296 μm to 544 μm.[44] EG&G Ortec specifies that a bias voltage of $\sim$70 V creates a depletion layer thickness of 100 μm or greater, the exact value depending on the silicon resistivity and the applied bias voltage.[2]

We also studied 4 Tennelec partially depleted model PD-50-100-17 diodes,[45] as well as 2 United Detector Technology (UDT) model PIN-8LC Schottky barrier diodes[46] (Table II). The Tennelec detectors have a 250 Å gold front surface on $\sim$400 μm thick silicon wafers, such that a bias voltage of $\sim$80 V creates a depletion layer thickness of $\sim$100 μm. The UDT diodes have 200 Å of gold over $\sim$250 μm thick silicon such that a bias voltage of $\sim$85 V creates a depletion layer thickness of $\sim$100 μm. Because the UDT detectors are primarily intended for use as optical photodiodes, the entire assembly is covered with $\sim$600 μm of standard borosilicate glass, rendering them blind to soft X rays; however they do respond to the higher energy X rays at 8 and 17.5 keV.

Ib. X-ray Source

The X-ray source used for these measurements was a Norelco model 12045 X-ray diffractometer. We used either a copper or molybdenum anode tube with a fixed mica window (nominally 13 μm thick) to produce predominantly Cu Kα and Kβ X rays at 8.05 and 8.9 keV respectively, or Mo Kα and Kβ X rays at 17.48 and 19.6 keV respectively. The high voltage was full-wave-rectified such that the diffractometer produced two distinct 60 Hz X-ray peaks (Fig. 1). The voltage could be varied up to 40 kV, and the emission current ranged from 1 to 15 mA.

The unfiltered spectrum from the diffractometer, as viewed directly through the mica window, consisted of the Kα and Kβ lines of the anode material as well as a significant amount of thick target bremsstrahlung. To provide "clean" spectra (*i.e.*, mainly K lines) for the calibration measurements, the diffractometer was filtered with the same material as the anode (33 mg/cm^2 copper foil for the Cu tube; 191 mg/cm^2 molybdenum foil for the

Mo tube). The K lines thus obtained made up at least 90% of the total number of photons collected (Fig. 2). The intensity of these lines was also measured to be linear with the diffractometer emission current (Fig. 3), an important consideration which subsequently bears upon the SBD linearity with X-ray intensity.

The intensity of the X-ray spectrum from the diffractometer was measured using either an EG&G Ortec or a KeVex Si(Li) X-ray spectrometer (Fig. 2). The spectrometer was gated to collect photons only during a 0.5 ms period at the larger of the two peaks (Fig. 1). The signal to gate the spectrometer was taken from a "monitor" SBD, which also served to assure a steady source strength over time. To avoid dead-time effects in the spectrometer counting system, the Si(Li) detector was filtered with material of known transmissivity. During the 8 keV measurements the spectrometer was covered with 233 ± 3.5 mg/cm^2 of copper foil, while during the 17.5 keV work it was covered with 636 ± 15 mg/cm^2 of molybdenum foil. (These thicknesses were determined by X-ray transmission measurements, using the absorption cross sections of References 47 and 48.)

Ic. Circuitry

The X-ray response current of the SBDs was measured using the two circuits shown in Fig. 4. The circuit of Fig. 4a is a low-noise current-to-voltage amplifier with the gain set by the 1 MΩ feedback resistor. The SBD bias voltage is fixed by the Zener diode to be -9 V. This circuit is convenient for plasma X-ray imaging systems,[17,18] and for making the absolute SBD response measurements reported herein. The rms noise level of this SBD/circuit combination is in the 1 nA range; consequently, the minimum practical signal measurable with this system is about 5 nA (corresponding to $\sim$.02 μW of incident X-ray power or $\sim$1.4$\times$10^7 photons/sec at 8 keV).

The simple circuit of Fig. 4b was used for establishing SBD linearity and the effects of varying the detector bias voltage. For example the value of the bias voltage was easily

varied over a wide range up to the maximum recommended by the manufacturer (~70 V); in addition the bias polarity could be trivially switched for use with different diodes (the Ortec diodes require a negative bias [p-type silicon]; the Tennelec and UDT diodes require positive bias [n-type silicon]).

IIa. Relative Diode Responses

The responses of the 18 Ortec diodes to 8 keV X rays were comparatively uniform. The maximum variation between the diodes was ~12% (Fig. 5a).[49] The signal current of each diode also exhibited a linear behavior from 0.1 to 150 μA with source intensity. (The 150 μA response corresponds to the maximum flux of X rays the diffractometer can generate.) Figures 6a and 6b show this linearity for two different filters and source voltages. The response of all these diodes was also independent of the bias voltage from the maximum recommended by the manufacturer down to about 1 V (Fig. 7a).

The Tennelec and UDT diodes were also very uniform at 8 keV. The maximum variation between the 4 Tennelec diodes was ~3%, and the 2 UDT diode responses were essentially identical to each other. The Tennelec SBDs also exhibited linear response (0.1 to 160 μA) with the diffractometer emission current, and the responses of both the Tennelec and UDT detectors were again independent of the bias voltage above 1 V (Fig. 7a).

The responses of the 18 Ortec SBDs to 17.5 keV X rays were much less uniform than at 8 keV. The maximum variation between the diodes at this higher energy was ~100% (Fig. 5b), which we attribute largely to differences in the physical thickness of the diodes. The SBD current was linear from 0.1 to 100 μA with the diffractometer emission current (Figs. 6c, 6d), and again independent of the bias voltage from 1 to 70 V (Fig. 7b). The comparative invariance of SBD responses with changes in bias voltage is particularly significant at 17.5 keV; the signal current should change drastically (by a factor of ~5) as the bias is varied from 1 to 70 V if the X-ray sensitive depth were determined by the

depletion depth. Instead it changes by less than 10%.

The Tennelec diodes exhibited larger variations in response to the higher energy X rays as well, while the 2 UDT diode responses were again virtually identical to each other. The maximum variation between the Tennelec diode responses to 17.5 keV X rays was ~15%. The responses of the Tennelec (at least 0.1 to 120 μA) and the UDT (at least 0.1 to 20 μA) SBDs were linear with the diffractometer emission current. The diode currents were again comparatively invariant to large changes in the effective bias voltage (Fig. 7b).

IIb. Absolute Diode Responses

The absolute response (defined as the current produced per incident power) of the 18 Ortec SBDs was measured at 8 and 17.5 keV. The intensity and spectra were measured with a Si(Li) spectrometer as described in Section Ib, and the response of the SBD was measured at the same physical location. At these energies it was necessary to aperture the SBDs with stainless steel washers to prevent the X rays from penetrating the epoxy which defines the outer edge of the active area of the diode (specified as 0.5 cm^2 by the manufacturer). Penetration of the epoxy would increase the effective area of the SBD. In particular, we measured an increase of ~30% in the response at 8 keV when the diodes were not apertured and the epoxy penetration was not accounted for.

The uncertainty in absolute response measurements arose from three main sources: spectral purity; the reproducibility of a set of measurements; and uncertainty in the transmissivity of the material used to filter the spectrometer. The uncertainty due to spectral purity (whether the SBD and spectrometer were responding to the same spectrum) was determined by taking measurements with and without a filter of known transmissivity that was sufficiently attenuating to reduce the incident X-ray power by a factor of 2. The difference between such filtered and unfiltered responses of the SBD and spectrometer always agreed within ±10%. The reproducibility between sets of measurements (*i.e.*, all 18

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diodes) was also always within ±10%. The uncertainty in the filter transmissivities for the Si(Li) spectrometer led to the largest uncertainties in absolute responses. (+16%, −20% at 8 keV; and +24%, −32% at 17.5 keV). The overall uncertainty (taken to be the square root of the sum of the squares of these contributions) was then +21%, −24% at 8 keV; and +28%, −35% at 17.5 keV.

In Fig. 5 the measured absolute responses are shown as a function of detector physical thickness, and in Fig. 8 as a function of photon energy (for comparison, responses of many of the same SBDs from Reference 15 are included). The measured responses agree well with predicted responses at 8 and 17.5 keV if the sensitive thickness is taken to be the physical thickness of the device; they do not agree if the sensitive region is taken to be the depletion layer thickness as determined by the bias voltage. These results are also directly relevant to fully depleted SBDs operated in an underbiased mode, since such detectors are, as mentioned, then partially depleted in actuality.

III. Summary of Findings; Discussion

The response of the SBDs to X rays at 8 and 17.5 keV was found to be linear from 0.1 μA to at least 100 μA. This agrees qualitatively with the results of Reference 15, where the SBD response to 1.5 keV X rays was shown to be linear over a factor of 4 in the 10 nA region. Incorporation of these results into ours indicates that SBDs are likely to have a linear behavior from ~10 nA to 100 μA. Diode linearity was found to be invariant to large changes in the bias voltage, and the smaller the signal current, the lower the bias could be set before bias-dependent effects became prominent (Fig. 7). It is interesting to note, however, that a bias-dependence was observed in the SBD response to fast (~50 ns) pulses of broadband X rays in the 50-100 keV range.[50] We believe this result is primarily caused by a frequency cutoff due to the bias-dependent capacitance of the SBDs, particularly because we saw no such bias-dependence for the response of the same diodes to 17.5 keV X rays modulated at 120 Hz.

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The lack of a significant bias dependence at 8 and 17.5 keV also has important implications for practical operational aspects. The leakage current, which often must be compensated for to maintain the maximum electronic dynamic range,[24-26] increases with bias (approximately as $\sqrt{V_{BIAS}}$). Therefore it is desirable to operate at a low bias to avoid a high leakage current due, for example, to an elevated diode temperature or diode degradation.[51] This work shows that low bias operation of partially depleted SBDs is in principle viable, and might be an acceptable means of reducing leakage current without affecting the high-energy X-ray response.[52]

Differences between SBD responses are comparatively small at 8 keV due to the large optical thickness of the diodes at this energy. The differences at 17.5 keV, however, are significant, because the diodes are not optically thick to photons of this energy. We also found the absolute response measurements agreed well with predicted responses if the X-ray sensitive thickness is assumed to be the physical thickness of the SBD (not the depletion layer thickness) and that the energy necessary to create a charge pair is 3.6 eV.[53-57] The absolute responses at 8 keV also agree well with those of Reference 15 reduced by 30% to correct for the effect of epoxy penetration discussed in Section IIb. This indicates a notable stability of the diodes over a period of 10 years. (The effect of X-ray penetration of the epoxy does not occur for the measurements at 0.282 and 1.5 keV of Reference 15.)

While agreement with predicted responses was within the errors for all 18 diodes, 3 new diodes in this group (26-454B, 26-454C and 26-454F; circled in Fig. 5) exhibited responses lower than expected based on their nominal thicknesses[58] (~10% at 8 keV and ~25% at 17.5 keV). One obvious difference between these diodes and the others is that their resistivity is typically a factor of 5 higher (Table II), which implies a depletion layer thickness about a factor of 2 greater.[2] We do not understand why these diodes have lower responses, but it is of central importance to this paper that this is additional evidence that the depletion depth is not the critical parameter in determining the X-ray sensitive region

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of SBDs.

Thus there are several issues which need to be addressed in future work. First, the logical extension of these results is to measure the response of SBDs to higher energy monochromatic X rays ($h\nu \simeq 25\text{-}100$ keV), again searching for any bias-dependence of the SBD signal. Second, it would be useful and interesting to directly test whether, as expected, fully depleted SBDs with a lower applied bias respond in the same fashion as partially depleted diodes, a comparison currently relevant to ongoing fusion experiments (Table I). Third, a comparison of the behavior of PIN and SBD diodes, specifically an examination of what constitutes the sensitive thickness of a PIN diode, will be important for future plasma experiments.[59,60] Finally, it is important that a physical explanation be sought as to why the X-ray sensitive depth is generally different from the depletion depth.

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49. Differences larger than $\sim 5\%$ between the diodes are real and unexplained: since 8 keV X rays easily penetrate the front diode surface, it is unlikely that the differences seen at this energy can be accounted for by differences in the front surface transmissivity. On the other hand, the optical depth is so large that the differences are not due to differences in the physical thickness either.

50. Using diodes #18-365G and #16-661G, Dr. Ruth Shefer of Science Research Laboratory has observed a bias voltage dependence of the SBD response to extremely fast (characteristic time $\sim$20 ns; total signal duration $\sim$ 140 ns) pulses of broadband X rays with energies greater than about 50 keV. We believe that this is due to a frequency cutoff effect due to the capacitance of the diode, which varies as $1/\sqrt{V_{BIAS}}$. With the 50Ω load resistor used by Dr. Shefer, the 3 db attentuation frequency of these diodes is $\sim 10\sqrt{V_{BIAS}}$ MHz. Furthermore, using the same diodes, we saw no such bias-dependence in the response to 17.5 keV X rays modulated at 120 Hz.

51. Among many other reasons, diode degradation can be caused by operating in a hydrogenated (reducing) atmosphere, or caused by radiation damage resulting in lattice defects. Degradation of SBDs due to neutron-induced damage from high temperature plasmas may possibly be avoided by using reflective optics. Annealing SBDs is not currently a useful method to remedy radiation damage because the epoxy used to construct the diodes cannot withstand elevated temperatures.[44] A. W. Edwards, et. al. found that most neutron damage in PIN diodes could be overcome by annealing.[34]

52. Two conditions must be met to allow low-bias operation of SBDs: 1) the X-ray signal must not have a characteristic frequency greater than the cutoff frequency of the SBD;[50] and 2) the signal amplitude cannot be so large that bias-dependent effects are prominent at low bias voltages (Fig. 7).

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57. R. D. Ryan, IEEE Trans. Nucl. Sci. NS 20, 1, 473, 1973.

58. The 26-series of Ortec SBDs have reported nominal thicknesses of 530 μm.[44] Using transmission of the 17.5 keV Mo Kα line we measured the thickness of diodes #26-454C to be 495±15 μm.

59. Measurements of the absolute X-ray response of fully depleted PIN diodes have previously been made at several photon energies. Ebert and coworkers did not examine the effect of varying the bias voltage. Private communications, 1987; and P. J. Ebert, J. L. Gaines, G. R. Leipelt, Nucl. Instr. and Meth. 99 29, 1972.

60. In so far as the low energy X-ray response ($\lesssim$2 keV) is unimportant in an experiment, PIN diodes may be preferable to SBDs because of their inherently faster time

response[50] and their capacity for annealing.[34]

Table I

Diode Type	Depletion F or P	Experiment	n_e (10^{13} cm^{-3})	T_e (keV)	Refs
SBD	F	ST (tokamak)	~7	~0.8	12
SBD	F	PLT (tokamak)	2~4	1~2	13
SBD	P	Tosca (tokamak)	1.5	0.2	14
SBD	P	Alcator-A (tokamak)	20~60	0.6~1.1	15,16
SBD	F	HBTX 1A (RFP)	2~20	~0.2	8
SBD	P	TEXT (tokamak)	1~9	0.7~1.1	17-19
SBD	?	TFR (tokamak)	~10	1	20
SBD	P	Alcator-C (tokamak)	10~100	1~3	21
SBD	P	ISX-B (tokamak)	0.5~9	0.5~2.2	22
SBD	P	HT-6B (tokamak)	0.7~1.2	0.1~0.12	23
SBD	P	ZT-40M (RFP)	~2	0.2	9
SBD	P	TFTR (tokamak)	~2	1~7	24-26
SBD	?	W VIIA (stellarator)	?	?	10
SBD	F	Constance (mirror)	~0.04	~400	11
SBD	?	Tokamak de Varennes	~5	~1	27
PIN	F	TFTR† (tokamak)	~2	1~2	28
PIN	F	DPF	$\lesssim 10^6$	~1	29
PIN	P	Ormak (tokamak)	2~4	1~1.5	30
PIN	F	Z pinch	$10^5 \sim 10^6$	6~9	31
PIN	P	Alcator-C (tokamak)	10~100	1~3	32
PIN	F	JET (tokamak)	~1.6	3~4.5	33,34
PIN	P	JT-60 (tokamak)	1~10	1~6	35
PIN	F	DPF	~10^6	0.2~0.5	36

Table I lists several representative plasma devices utilizing silicon surface barrier diodes (SBD) or P-Intrinsic-N (PIN) diodes to detect X rays. The detectors are intended for either full (F) or partial (P) depletion; however diodes capable of fully depleted operation can be run underbiased such that full depletion is not attained; in such circumstances the diode is actually operating in a partially depleted mode.

Note the wide range of plasma electron densities ($4 \times 10^{11} - 1 \times 10^{19}$ cm^{-3}) and temperatures (0.2-400 keV) for which these silicon-based detectors are useful. [RFP refers to reversed field pinch; DPF refers to dense plasma focus.] † The PIN array on TFTR was not operational for the "supershots" for which the electron temperature was ~7 keV.

Table II

Diode #	Thickness (μm)	Resistivity (Ω-cm)
EG&G Ortec:		
*16-846F	296	6800
*16-663I	321	3000
*16-663F	321	3000
18-365G	322	2500
16-662H	335	3000
*16-662D	335	3000
*16-662C	335	3000
*17-230E	347	4000
16-675C	347	3700
*16-675B	347	3500
*16-850J	347	3500
18-312C	484	3000
*16-821A	544	3500
*16-821C	544	3500
*16-821J	544	3500
26-454B	530	15700
26-454C	530	15700
26-454F	530	15700
Tennelec:		
4226-5	400	2100~3000
4013-9	400	2100~2400
4020-14	400	2100~2400
4170-11	429	2100~2400
UDT:		
PIN-8LCA	250~380	400
PIN-8LCB	250~380	400

Table II lists the partially depleted silicon surface barrier diodes (SBD) used for the measurements reported herein. Eleven of the SBDs(*) are the same diodes used in References 15,16, and 21. The nominal physical thickness of the silicon and its resistivity (which, in combination with the bias voltage, determines the depletion depth) are also listed.[44-46]
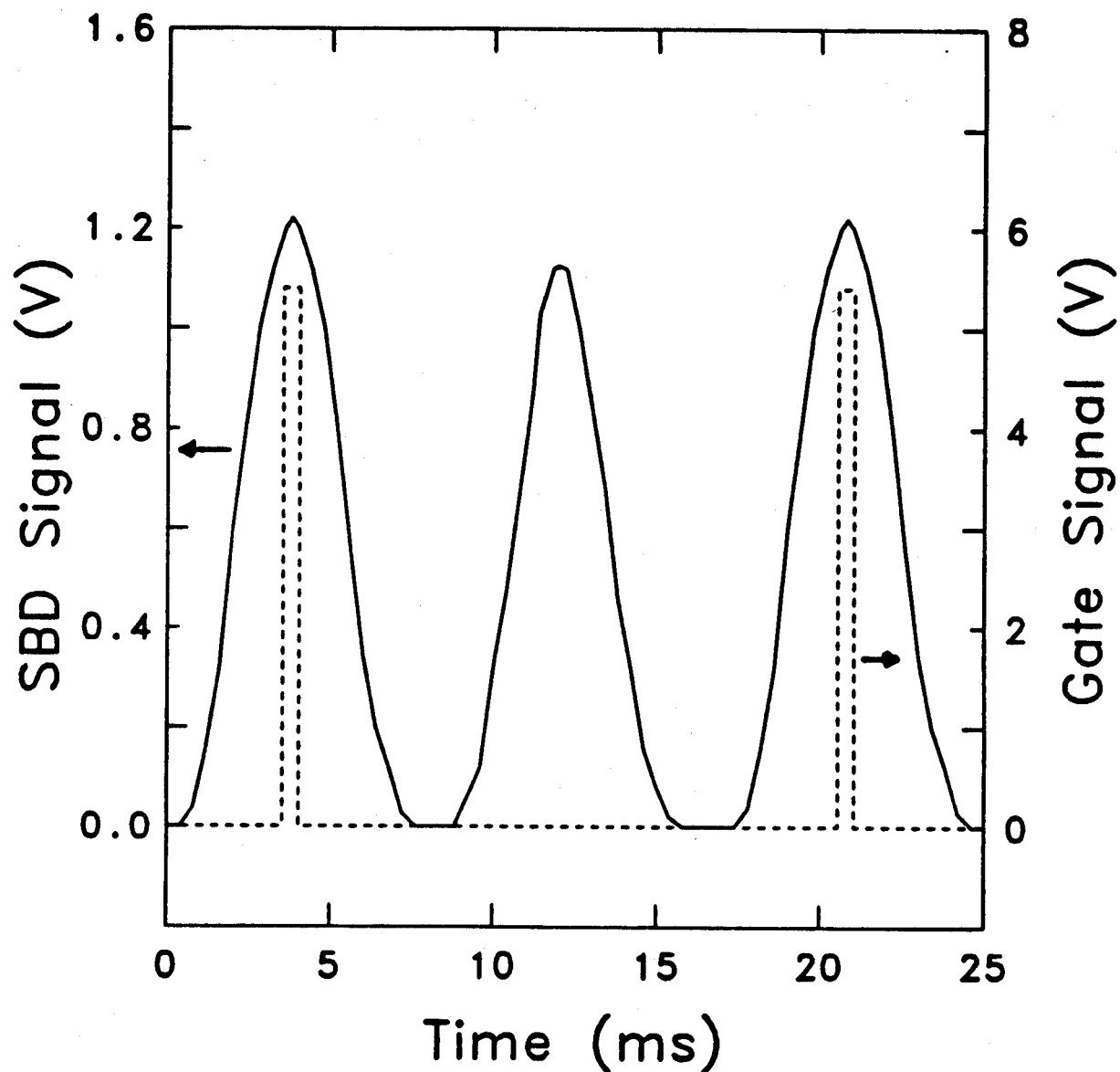
Fig. 1. Typical SBD response to the Norelco diffractometer with the copper tube installed. The high voltage of the diffractometer is full-wave-rectified, generating two distinct 60 Hz X-ray peaks of slightly different amplitude. The square wave (dashed) is triggered on the larger SBD signal; it is subsequently used to gate a Si(Li) spectrometer so that it only counts photons during the 0.5 ms period during the peak of the X-ray emission.
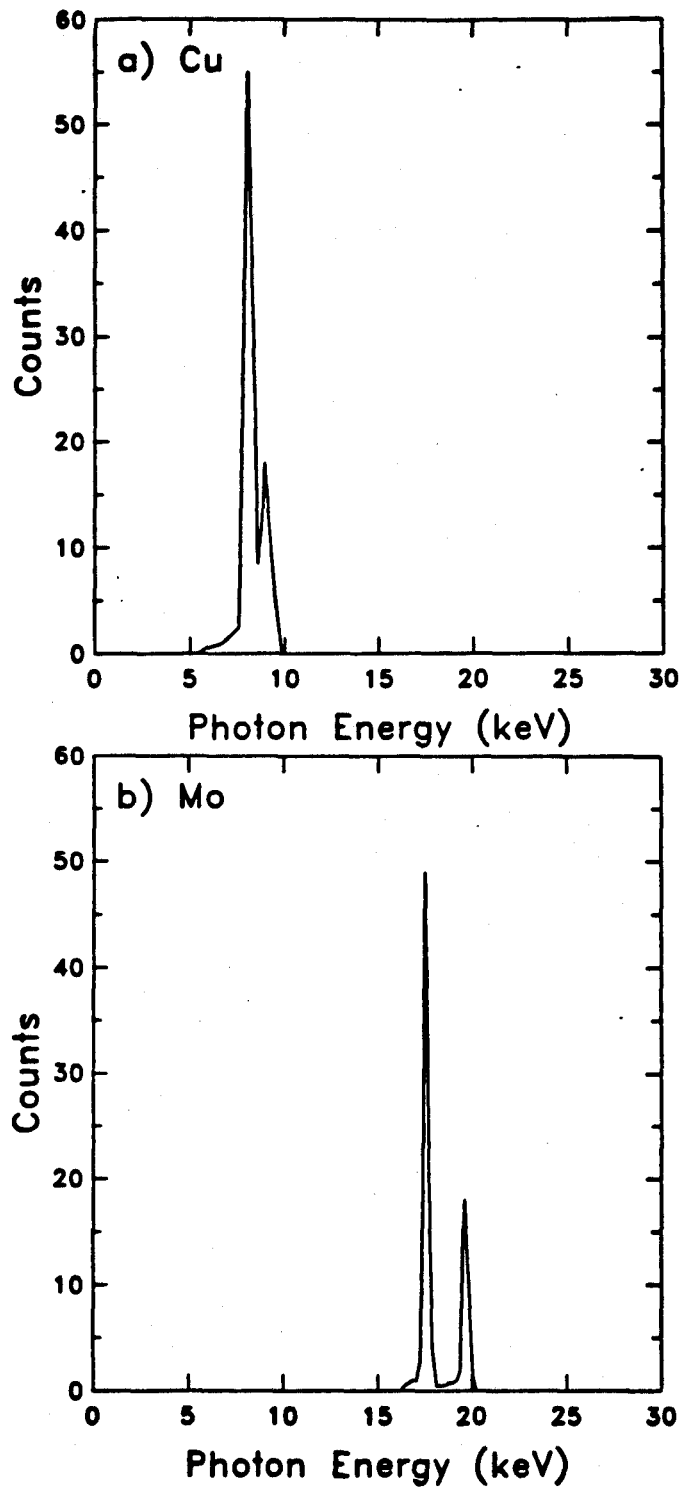
Fig. 2. Spectra used for the SBD calibrations as measured by a Si(Li) spectrometer. a) The copper K lines make up about 90% of the total counts when the diffractometer is run at 15 kV and filtered with 33 mg/cm² copper foil. b) The molybdenum K lines comprise about 90% of the total number of photons when the diffractometer is run at 40 kV and filtered with 191 mg/cm² molybdenum foil.
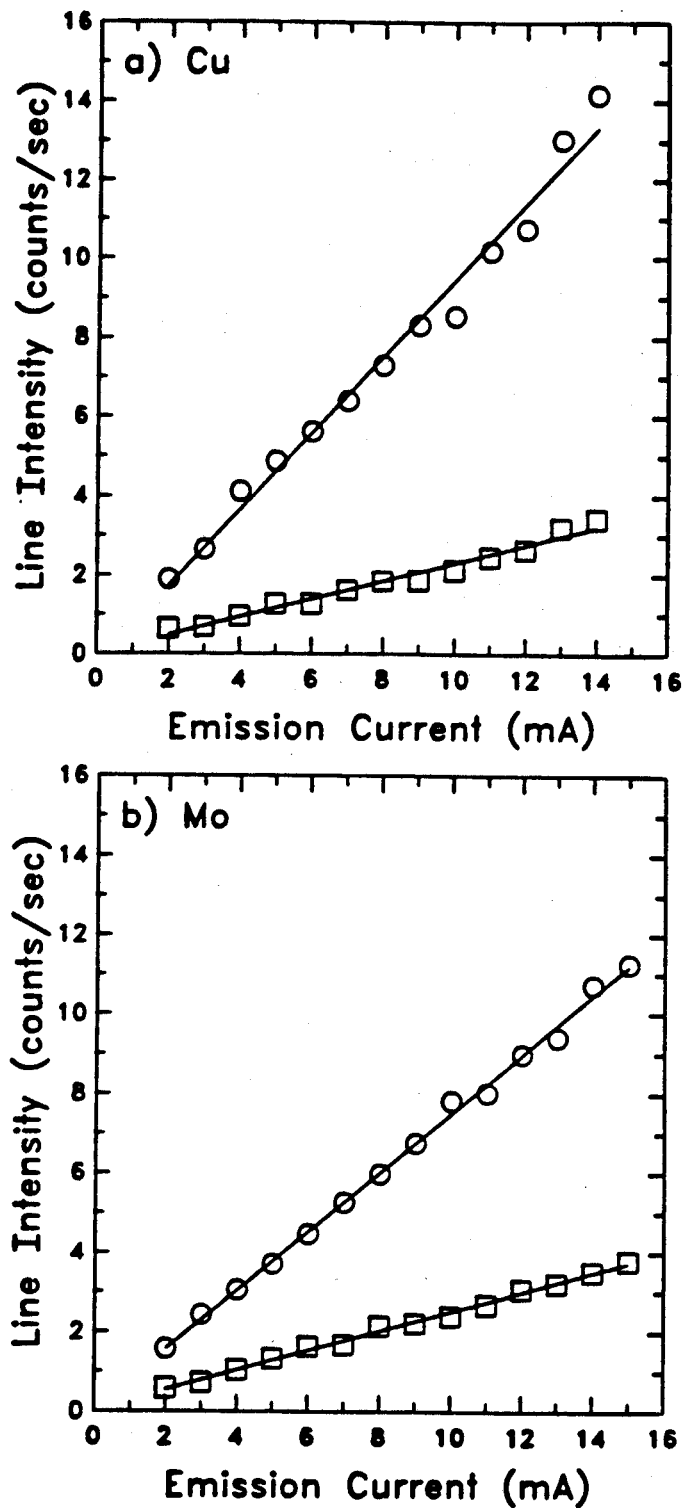
Fig. 3. The intensity of the spectra used for the absolute SBD calibrations is linear with the diffractometer emission current, an important fact used later to determine SBD linearity. a) Linearity of the Cu Kα (circles) and Kβ (squares) lines when the diffractometer is run as described in Fig. 2a. b) Linearity of the Mo Kα (circles) and Kβ (squares) lines when the diffractometer is run as described in Fig. 2b.
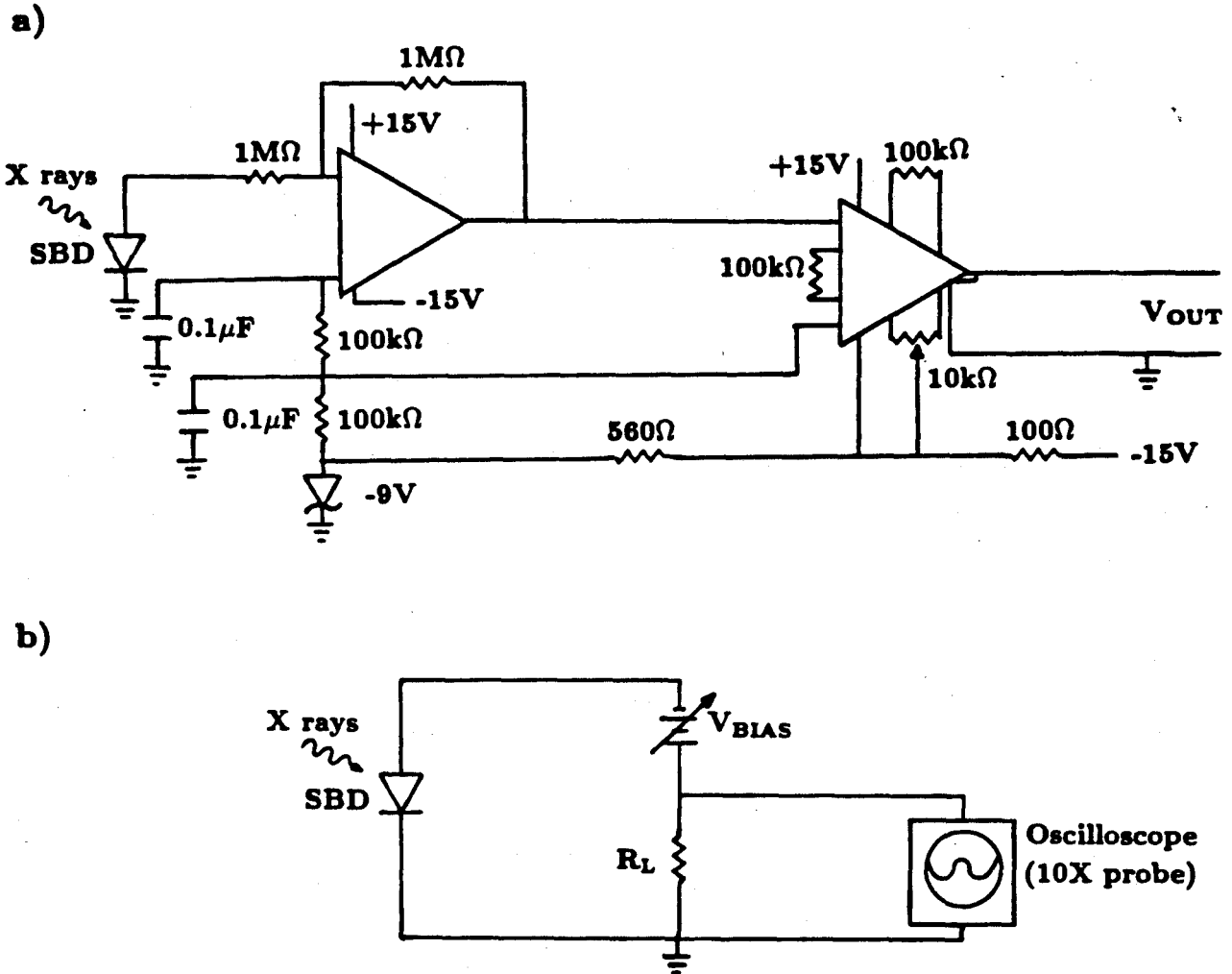
23

a)

b)

Fig. 4. Two circuits used to measure the SBD response current. a) This circuit has been used for an X-ray imaging system on the TEXT tokamak[17,18], and for all absolute SBD calibration measurements reported herein. b) This simple circuit was used for making linearity measurements (where a wide range of response currents made it desirable to change the gain [R_L] easily), and for examining the effects of changing the SBD bias voltage (though not the results shown in Fig. 7). In this configuration, it is important that V_{BIAS} exceed the voltage drop across the load resistor; this guarantees a non-zero effective bias voltage on the SBD. For the linearity measurements the gain was adjusted so as to insure the voltage drop across the load resistor was much smaller than the applied bias voltage.
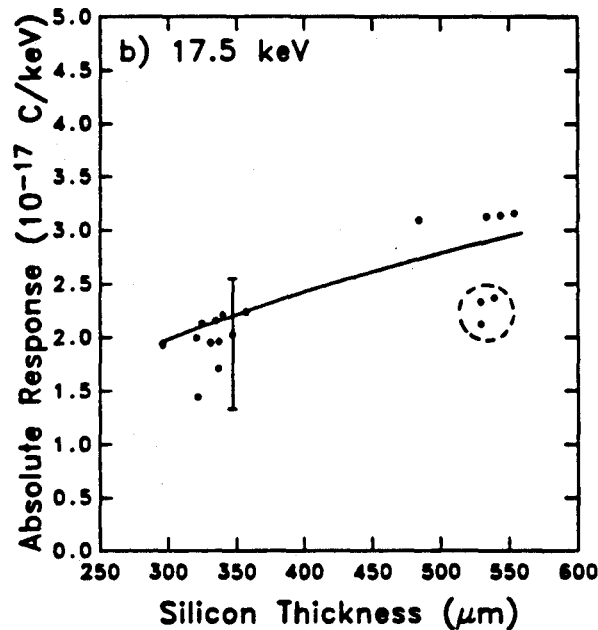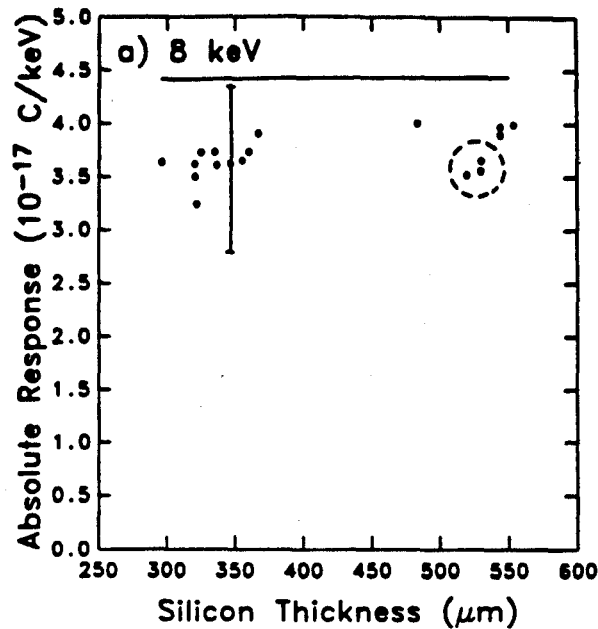
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Fig. 5. The measured absolute responses (points) are compared to predicted responses (lines) based on the physical thickness of the SBD, not the depletion depth, and assuming 3.6 eV in order to create an electron-hole pair[53-57]. The predicted response is proportional to $(1 - e^{-\mu\rho t})$ which is $\simeq 1$ and nearly constant at 8 keV; but at 17.5 keV it varies rapidly with thickness. Relative differences greater than $\sim 5\%$ between diodes are real. The repeatability of an entire set of measurements (all 18 diodes) is $\pm 10\%$. Some of the data points have been displaced from their nominal thickness by up to 20 μm to avoid overlap. a) Absolute response to Cu K X rays (spectrum of Fig. 2a). b) Absolute response to Mo K X rays (spectrum of Fig. 2b).
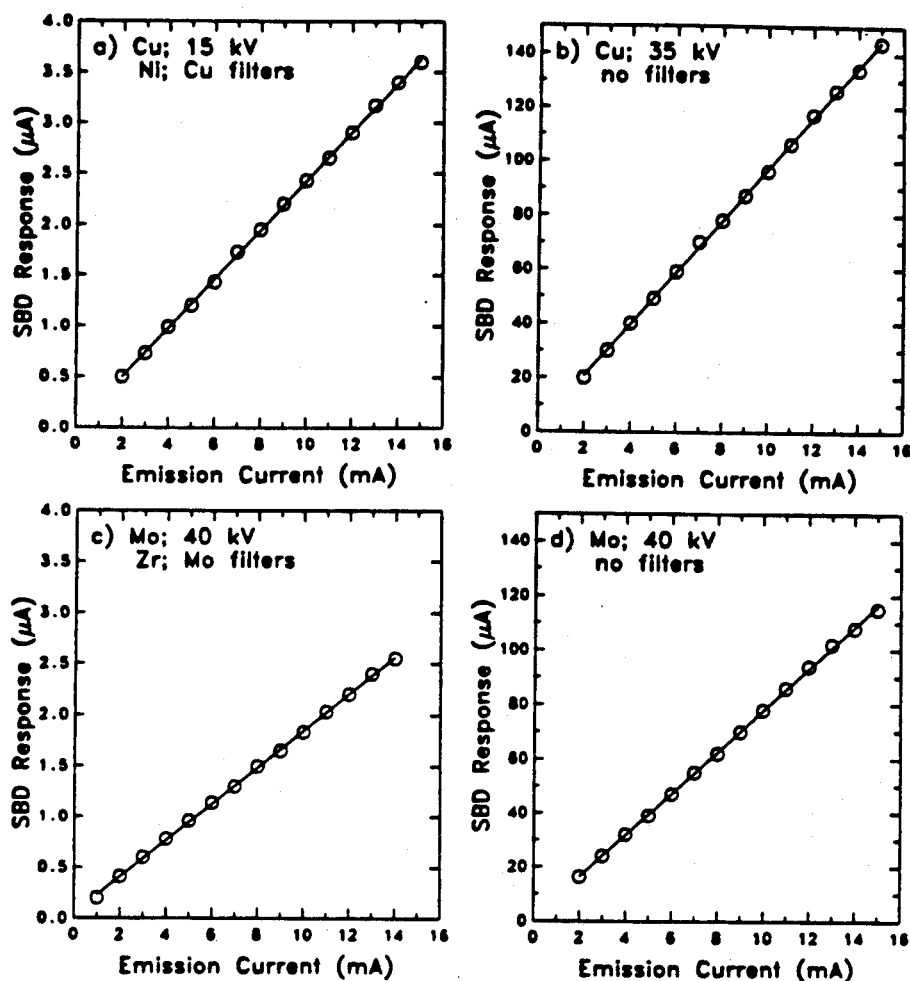
Fig. 6. The SBD signal current is linear with the diffractometer emission current, and therefore with incident X-ray power (see also Fig. 3). a) Linear response when the diffractometer has the copper tube installed, when it is run at 15 kV and is filtered with 17 mg/cm^2 nickel and 33 mg/cm^2 copper foil. b) Linearity when the diffractometer has the copper tube installed, is run at 35 kV, and with no filtering except the fixed mica window of the tube. 150 μA is the maximum signal current that can be generated using the diffractometer as the source. c) Linear response when the diffractometer has the molybdenum tube installed, when it is run at 40 kV and is filtered with 66 mg/cm^2 zirconium and 64 mg/cm^2 molybdenum foil. d) Linearity when the diffractometer has the molybdenum tube installed, when it is run at 40 kV with no filtering except the fixed mica window of the tube.
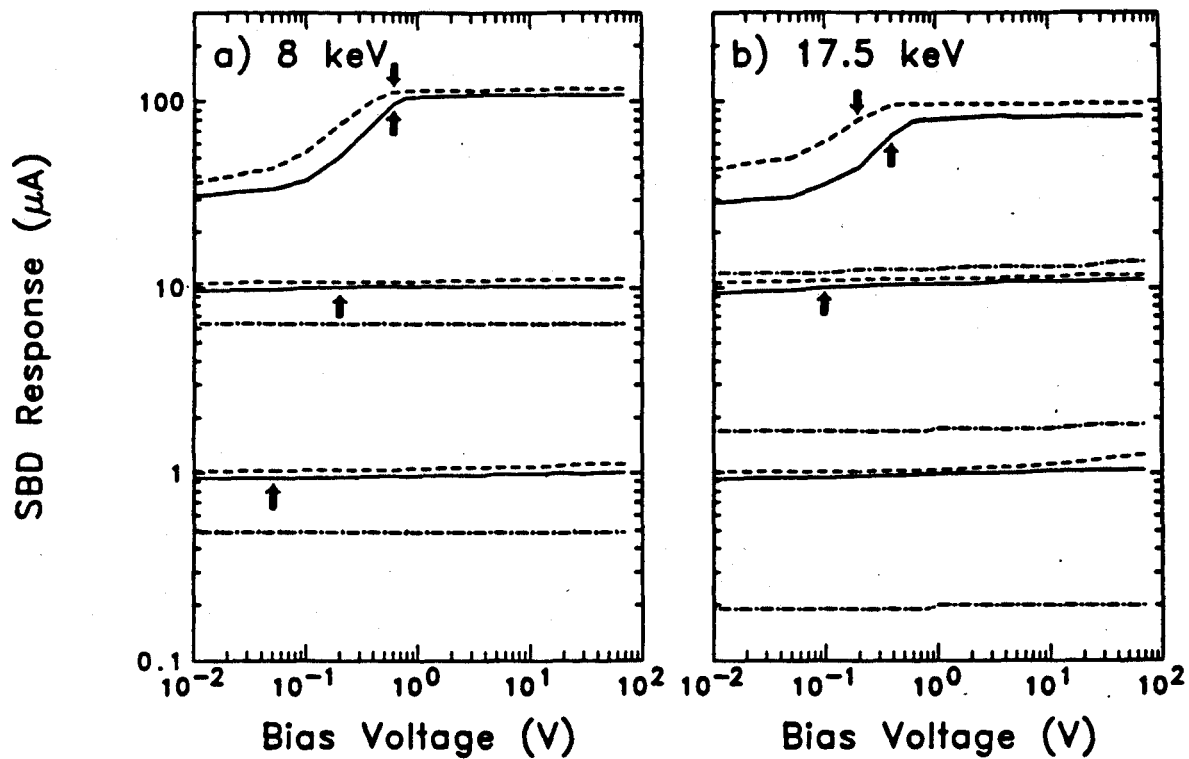
Fig. 7. Using a circuit similar to that shown in Fig. 4a, but for which the bias could be easily varied, the effect of large changes in the bias voltage on X-ray response was measured for three SBDs: EG&G Ortec #16-675C (solid line); Tennelec #4226-5 (dashed line); and UDT #PIN-8LCA (dot-dashed line). The Ortec and Tennelec diodes were examined for nominal signal currents of about 100, 10 and 1 μA (at 70 V bias). The corresponding UDT response ranged from 10 to 0.1 μA. The vertical arrows indicate bias voltage below which the response signal became distorted for the Ortec (↑) and Tennelec (↓) diodes; the UDT diodes did not exhibit any distortion in this range of signal currents.

a) The responses of the SBDs to 8 keV X rays was independent of bias voltage between ~1 and 70 V. A signal-dependent decrease in the response current was observed below a bias voltage of about 1 V. b) The responses of the SBDs to 17.5 keV X rays changed by <10% as the bias changed from 1 to 70 V. A signal-dependent decrease was again observed below about 1 V. The relative invariance of the SBD signal with such a large change in bias voltage is in contrast to the behavior expected if the X-ray sensitive depth were the depletion depth, which would give roughly a $\sqrt{V_{BIAS}}$ dependence for the SBD response.
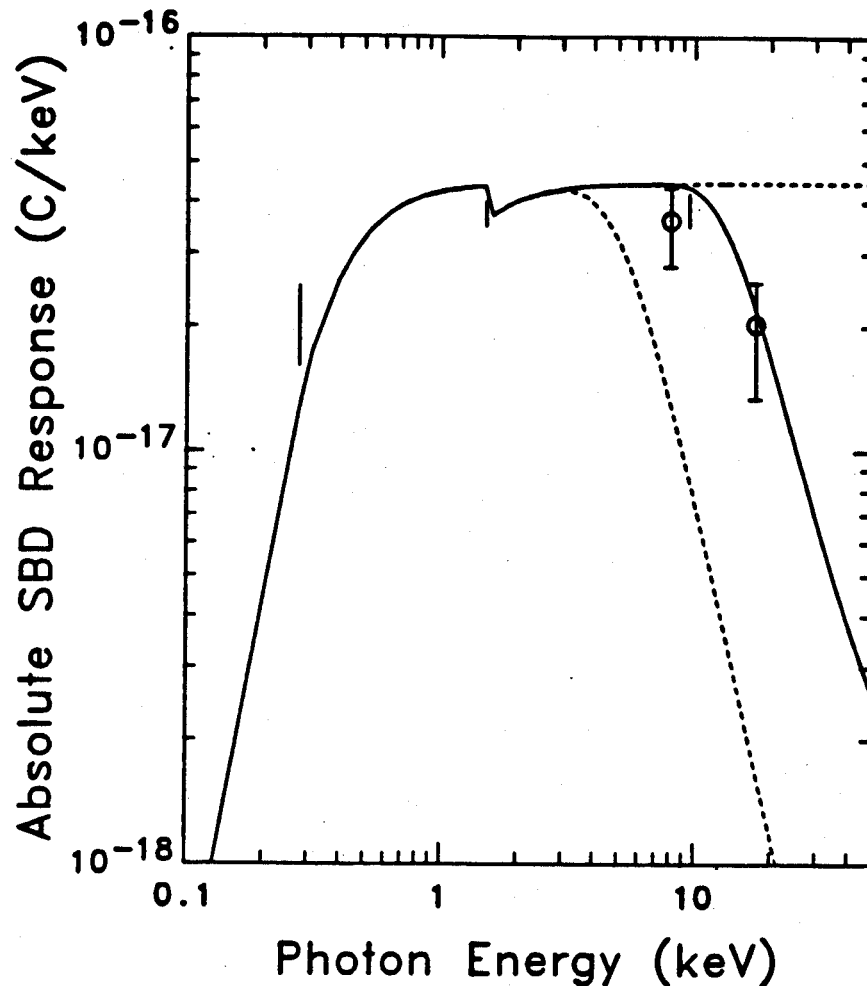
Fig. 8. Measured absolute responses are compared with predicted absolute responses as a function of photon energy. The two data points with error bars are the responses measured for the representative diode #16-675C. The solid vertical lines represent the range of results measured for many diodes in Reference 15. At 8 keV these results have been reduced by 30% to correct for penetration of the edge epoxy, an effect not taken into account in that work (the 8 keV data is also offset to 10 keV for clarity). The solid curve is the response predicted for a 347 μm thick detector (see Table II). The upper dashed line is the predicted response for a detector of infinite thickness, and the lower dashed line is the predicted response for a 20 μm thick detector (the depletion layer thickness of detector #16-675C at a bias of 1 V). The measured responses agree best with the theoretical response based on the physical thickness of the SBD.

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