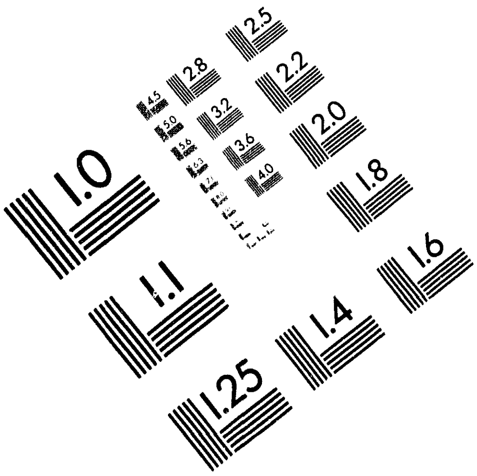

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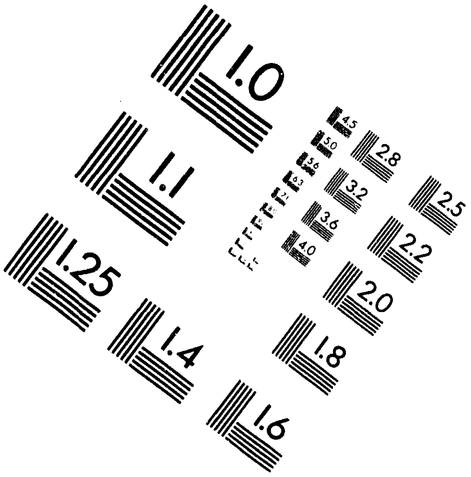

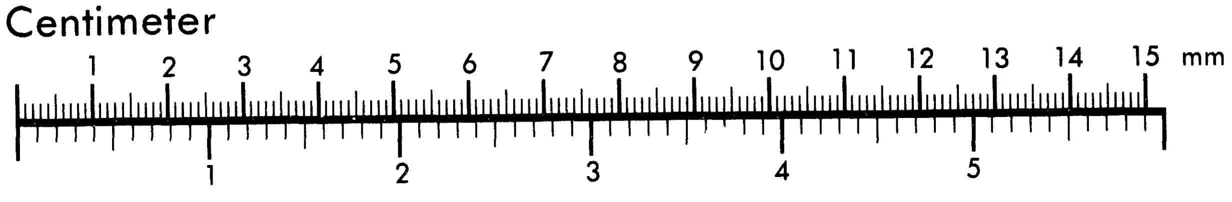

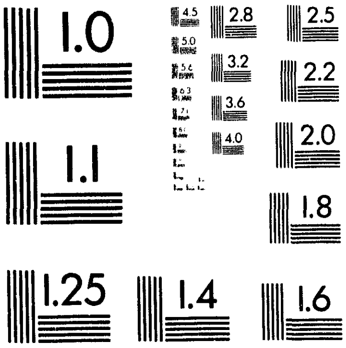

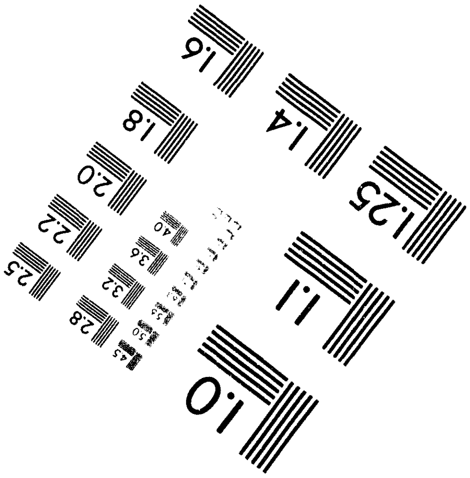

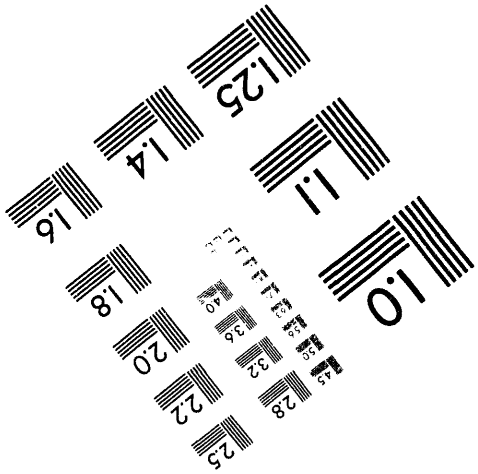

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ACTIVE SILICON X–RAY FOR MEASURING ELECTRON TEMPERATURE

by
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ABSTRACT

Silicon diodes are commonly used for x-ray measurements in the soft x-ray region between a few hundred ev and 20 keV. Recent work by Cho[1] has shown that the charge collecting region in an underbiased silicon detector is the depletion depth plus some contribution from a region near the depleted region due to charge-diffusion. The depletion depth can be fully characterized as a function of the applied bias voltage and is roughly proportional to the squart root of the bias voltage. We propose a technique to exploit this effect to use the silicon within the detector as an actively controlled x-ray filter. With reasonable silicon manufacturing methods, a silicon diode detector can be constructed in which the sensitivity of the collected charge to the impinging photon energy spectrum can be changed dynamically in the visible to above the 20 keV range. This type of detector could be used to measure the electron temperature in, for example, a tokamak plasma by sweeping the applied bias voltage during a plasma discharge. The detector samples different parts of the energy spectrum during the bias sweep, and the data collected contains enough information to determine the electron temperature. Benefits and limitations of this technique will be discussed along with comparisons to similar methods for measuring electron temperature and other applications of an active silicon x-ray filter.

INTRODUCTION

Silicon diodes are commonly used for x-ray measurements in the soft x-ray region between a few hundred eV and 20 keV.[2–6] Silicon diodes operated in the current mode (the absorbed photon rate is large compared to the characteristic detector/amplifier circuit time constant) have very good x-ray sensitivity (quantum efficiency very close to one) and very good frequency response (for example silicon detector diagnostics with amplifier gains appropriate for large tokamak plasmas typically have frequency response greater then 100 kHz). Silicon diodes operated in the current mode (for the remainder of this report the term silicon diodes will refer to silicon diodes operated in the current mode), used as a plasma diagnostic, have the drawback that the detected signal is a complicated function of the plasma electron density, temperature and atomic species. The x-ray emissivity from a plasma with a Maxwellian electron distribution can be written as[7–10]

$$I(E)=2.60\times10^{-14}\,\zeta n_e \Sigma_i n_i Z_i^2 (13.59\,\mathrm{eV}/T_e)^{1/2} e^{-E/T_e} \qquad (1)$$

energy/unit energy-s-cm^3. Where ζ is the x-ray enhancement factor due to impurities over a purely hydrogen plasma, n_e and n_i are the electron and ion densities respectively, Z_i is the ion atomic number and T_e is the electron temperature.

Techniques have been developed to try and extract the electron temperature from silicon diode signals using x-ray filters of varying thicknesses. The simplest of these methods is called the two filter method and, as the name implies, uses two different x-ray filters, each in front of a separate silicon diode.[11,12] Because the different x-ray filters have different x-ray absorption spectra, the two silicon diodes sample different parts of the emitted x-ray spectra. If the electron temperature is Maxwellian, then the electron temperature can be extracted from the two silicon detector signals. This technique has not been generally accepted as a reliable temperature diagnostic because of 1) of uncertainties in the calibrations between the two detectors and electronics, 2) differences in viewing geometry between the two detectors, 3) inherent uncertainties in fitting a temperature with only two data points, 4) dynamic range limitations of the detectors (caused by the requirement of very thick filters), 5) interfering impurity line radiation from the plasma, 6) high energy electrons in the plasma. In this report we discuss a technique that uses the silicon that makes up the detector as an x-ray filter. It has recently been shown that the thickness of the charge collection region in a silicon diode varies in a well defined way with the applied reverse bias.[1] By sweeping the bias on a single silicon diode, the effective thickness of the silicon is also swept, effectively producing an actively variable x-ray filter. The signal from such a sweep of the bias could be used to fit an electron temperature in a similar way as the two filter method only without the first four of the drawbacks listed above. The remainder of this report will describe in some detail the proposed technique and uses for the technique.

ACTIVE X-RAY FILTER

The diagnostic layout is shown in Fig. 1. The silicon diode is shielded from visible light and particles from the plasma by a thin metal foil of thickness F_x. X-rays emitted from the plasma are imaged by a slit onto the silicon diode with SiO_2 dead layer of thickness G_x. Within the silicon wafer there are three layers of interest to this discussion. As shown in Ref. 1, these three regions can be well characterized both experimentally and theoretically. The first is the depleted region shown in Fig. 1 as Region A, of thickness $d(V) = d_0 (V+1)^{1/2}$ where V is the reverse bias applied to the diode and d_0 is the depletion depth without an applied bias voltage. In this region, electron hole pairs that are created by absorbed x-rays are quickly swept out of the region and collected as signal. The second region, shown in Fig. 1 as Region B with thickness d_1, is a transition region between the depleted region and the rest of the substrate. In this region, electron hole pairs that are created by absorbed x-rays diffuse toward the depleted region and a large percentage of the charge is collected as signal before recombination occurs.[1] The finial region shown in Fig. 1 as Region C with thickness $d_2 = S_x - [d(v) + d_1]$ where S_x is the silicon wafer thickness, is insensitive to x-rays. In this region, electron hole pairs created by absorbed x-rays recombine before they diffuse into the depleted region and are not collected.

The response of the detectors A(E) (in absorbed photons per incident photon) is the product of the absorption of the silicon in the active region, with the transmission of the plasma facing filter and the detector front dead layer;

$$A(E) = T_F(E)\, T_D(E)\, \tilde{A}_S(E) \quad ,$$

where $\tilde{A}_S(E) = (1 - T_{S,A}) + (1 - \alpha T_{S,B})$, T_F and T_D are the transmission of the filter and the dead layer respectively, $T_{S,A}$ and $T_{S,B}$ are the transmission through Region A and B in the silicon active region and α is a correction fraction[1,6] due to recombination effects in Region B. The total current out of the detector is $I \propto \int_G \int_0^\infty A(E)\varepsilon(E,\mathbf{r})\, dE d\mathbf{r}$, where $\int_G d\mathbf{r}$ is the volume integral over the plasma viewed by the detector and ε is the x-ray emissivity of the plasma.

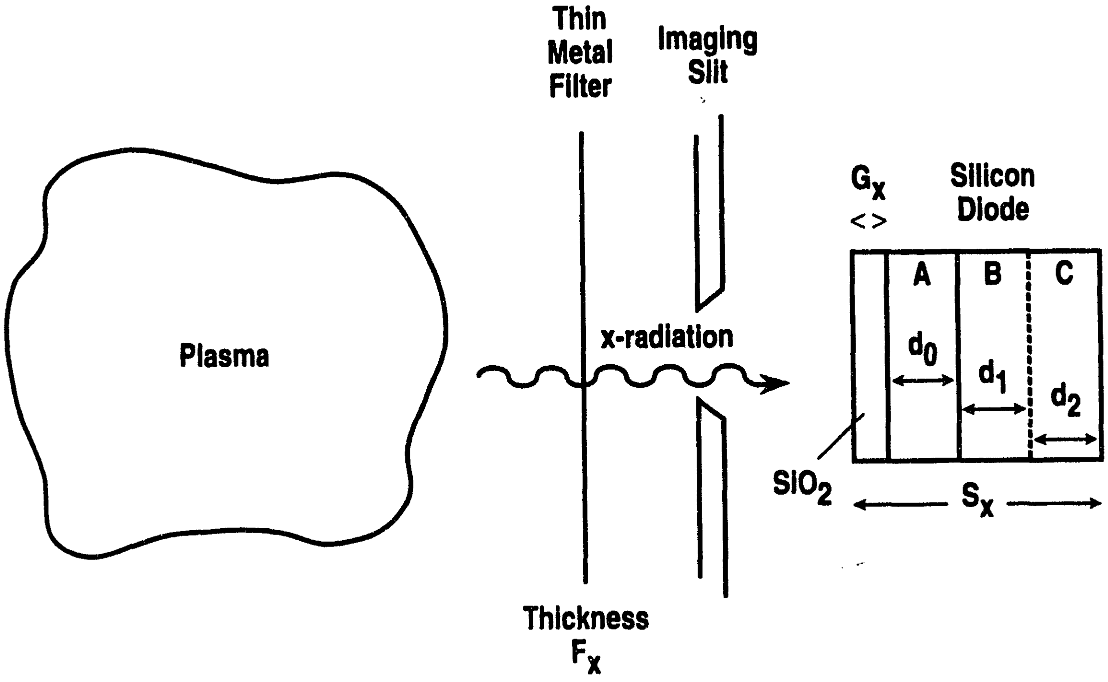

Fig. 1. Diagnostic layout. Changing the bias voltage on the detector changes the width of the active region d_0 and the spectral response of the detector.

By sweeping the reverse bias V from 0 to V_0 (where V_0 is the bias required to fully deplete the diode, typically 30–40 volts for high resistivity silicon of thickness 150 microns), the silicon active depth is continuously changed from roughly d_1 to S_x, which in turn continuously changes the x-ray spectral response of the detector. Figure 2(a) is a plot of the signal from a diode as a function of silicon active depth $(d_0 + d_1)$ which can be translated into reverse bias. Shown on the plot are a family of curves of the signal from the detector as a function of silicon active depth for plasma electron temperatures from

500 eV to 5 keV (each curve is normalized to the signal from a fully depleted diode). By reversing the silicon diode so that the depletion region faces away from the plasma (backlighting), the silicon dead region can be used as a variable x-ray filter. A plot of the family of curves from a backlight diode is shown in Fig. 2(b). By fitting such curves generated during a single sweep of the bias, a temperature can be extracted from the signal. Since a single diode is used to generate the curve, variations in calibration and viewing geometry are not an issue in interpreting the data. If a sweep is made in 1 ms with a sampling rate of 20 kHz, then 20 separate data points would be gathered and could be used in the fit. With a 20 kHz sampling rate using the DIII–D x-ray diagnostic as an example,[6] the noise on each data point should be less then 1% of the signal from the fully depleted diode for typical DIII–D plasmas.

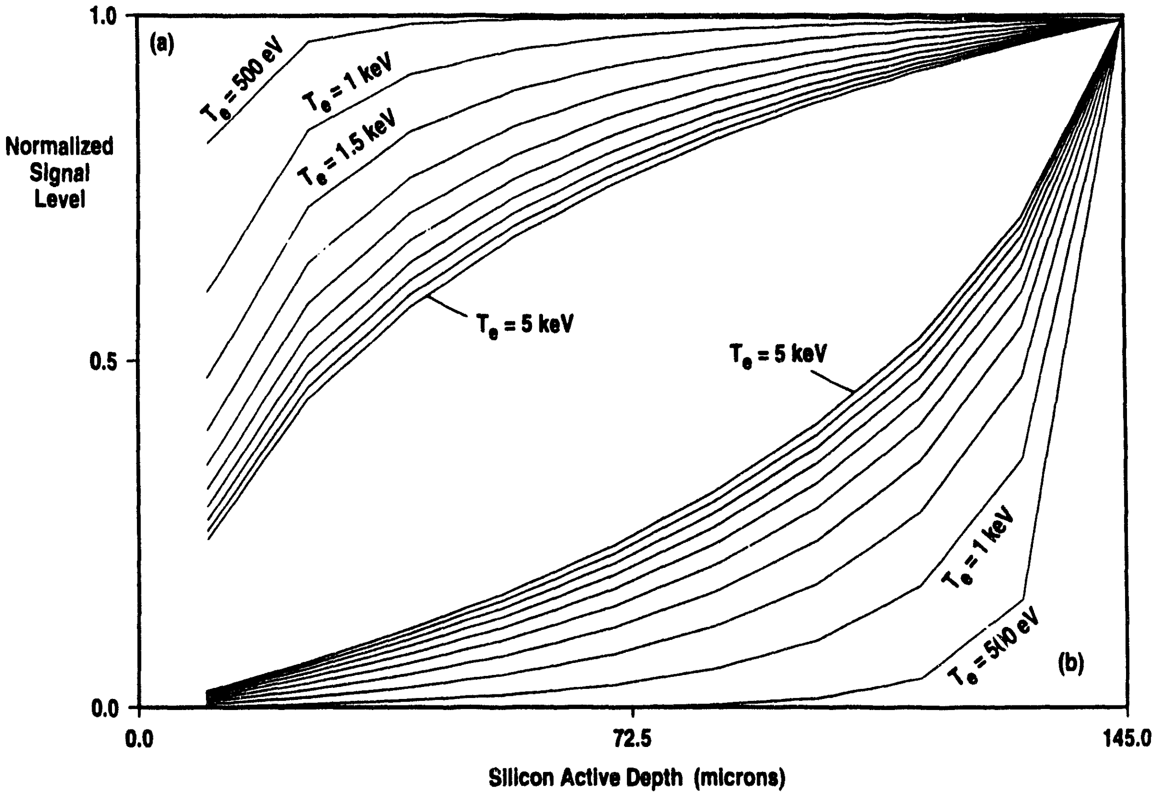

Fig. 2. Families of curves for various T_e. (a) Active region facing the plasma, (b) active region facing away from the plasma (backlight).

SOURCES OF ERROR AND ERROR ANALYSIS

Simulated spectra were calculated from Eq. (1). Random noise of 1% of the signal from a fully depleted detector was added to the signals calculated from the simulated spectra on each of 20 data points corresponding to 20 bias voltage levels. A least squares fit to the randomized data was used to estimate the error as a function of T_e. The result is displayed in Fig. 3 where the error bars are the estimated error in T_e from a 1% random error in the detector signal. As can be seen in the figure, the error increases at higher temperatures ranging as low as 1% below 3 keV to 5% at 10 keV. The increase in error at higher temperature is a result of the increasing transparency of the thin silicon detector at high x-ray energy. The dashed lines in Fig. 3 represent the bounds of the systematic error produced by a ±10% uncertainty in the thickness of F_x.

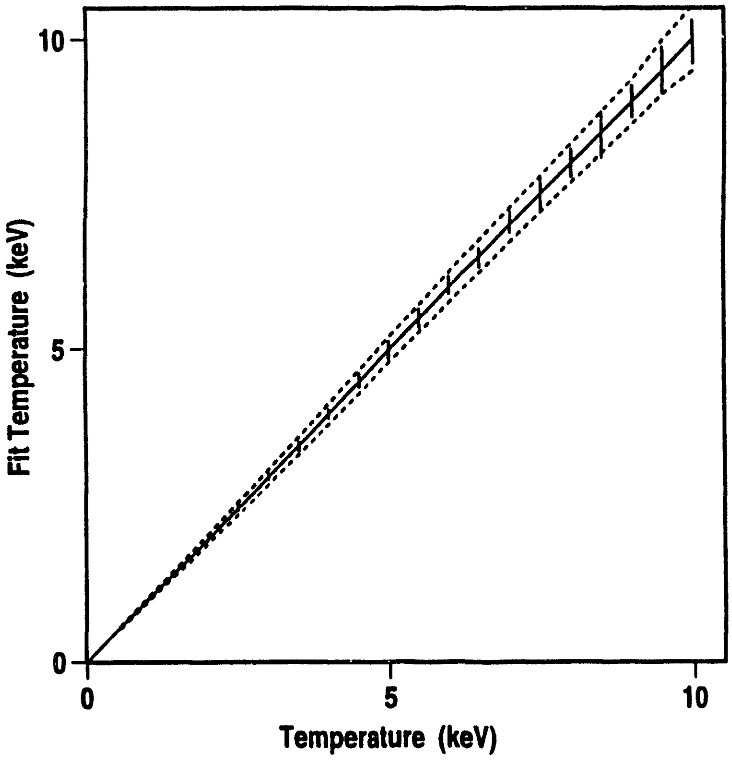

Fig. 3. T_e fit from 20 bias voltage levels from simulated spectra. The error bars are estimated from a 1% random error in the detector signal. The dashed lines represent the bounds of the systematic error from a ±10% uncertainty of the foil thickness (F_x).

Another source of potential error in this method is interferring spectral lines. However, in modern tokamaks wall condition methods produce very clean plasmas with very low levels of impurities with lines in the soft x-ray region of interest. An example of a typical DIII–D x-ray spectra produced by a Si (Li) pulse height detector is shown in Fig. 4 for an ohmic plasma. As can be seen in the figure, there are no significant spectral line and from this we conclude that spectral interference is not a concern, at least in DIII–D.

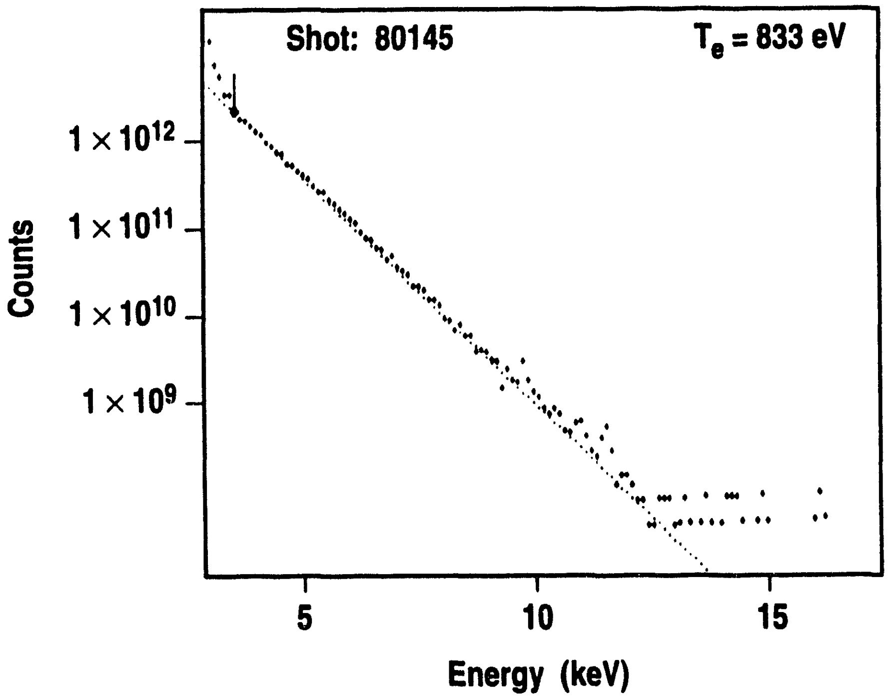

Fig. 4. DIII–D x-ray spectra from Si (Li) detector. No significant spectral lines are evident.

A further source of error comes from the line of sight integration through the plasma. This is common to all x-ray temperature measurements and the resulting error has been estimated in Ref. 13. The large number of channels used in typical x-ray imaging diagnostics that could take advantage of the temperature measurement method described here can reduce this error somewhat since a better spatial inversion of the data can be made.

APPLICATIONS AND DETECTOR REQUIREMENTS

As an example of how such a technique might be useful as a plasma diagnostic consider the DIII–D x-ray system.[6] A complete two dimensional temperature contour plot of the plasma could potentially be reconstructed every ms., by replacing just the existing detectors (see below for detector requirements) and the bias supply with a waveform generator, leaving in place all of the imaging hardware, signal conditioning electronics, and data acquisition

Another application of an active x-ray filter would be to use a backlight diode without a metal filter. A fully-depleted diode would be sensitive to visible, UV light, and soft x-radiation. Typically the signal from a diode without a metal filter is dominated by the UV for tokamak plasmas.[14] By reducing slightly the bias voltage to make the inactive region of the order 10 μm, the detector would then become insensitive to visible and UV light but remain sensitive to soft x-rays. This would allow the same diagnostic to view either the visible and UV or, by simply changing the bias, view the x-ray emission.

In order to maximize the range of thickness that can be controlled by V, d_1 should be minimized while avoiding breakdown in the diode when fully depleted. In general, d_1 is small in diodes made of low resistivity silicon (<2 kΩ-cm) or with proper impurity doping in high resistivity silicon (>4 kΩ-cm). High resistivity silicon is required to avoid breakdown at voltages near those needed for full depletion. There are some test results that indicate that diodes that can be fully depleted with high recombination rates (i.e. small d_1) are possible. In any case, in order for the detector to be useful for this technique,a complete characterization of the detector would be required similar to that described in Ref. 1 in order to measure d_1.

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