

1/f Noise in Doped Semiconductor Thermistors

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Abstract. We have characterized the $1/f$ noise in standard ion-implanted silicon thermistors, which are about 250 nm thick. We find that it is associated with the bulk of the implant, and is interpretable as a $\Delta R/R$ fluctuation that is independent of the bias and depends only on the doping density and resistivity, or electron temperature. This excess noise is large enough that it has a significant effect on the energy resolution or NEP of a detector using these thermistors. The very steep temperature dependence of the $1/f$ noise suggested that it might be related to the conduction becoming two-dimensional, and we have fabricated thicker detectors to test this hypothesis. Similar doped silicon thermistors that are 1500 nm thick show negligible $1/f$ noise, but otherwise behave identically to the thinner thermistors of the same volume. This simple change could provide a 40% improvement in resolution for some existing X-ray detectors.

INTRODUCTION

Ion-implanted semiconductor thermistors have advantages for fabrication in monolithic detector arrays, since they can be formed lithographically directly in the structural silicon. However, they suffer from a number of effects that limit the obtainable energy resolution to values less than predicted for "ideal" thermistors in the analysis of Moseley et al. where the only significant noise sources are thermodynamic fluctuations and the Johnson noise of the thermistor [1]. These effects are summarized in paper A21 in this volume [2]. They have all been characterized, so that detector designs can be optimized in their presence, and we have shown that the total noise in our detectors can be well accounted for by the sum of these known contributions [3]. In this paper, we describe the characterization of the intrinsic $1/f$ noise observed in "standard" silicon implants, and show that this particular noise source can be reduced to negligible levels by making the implants thicker.

STANDARD (THIN) IMPLANTS

Figure 1 shows noise spectra taken of an implant-doped silicon thermistor that is strongly coupled to a heat sink so that the lattice temperature is constant. With no bias current, the noise is white (except for the drop at high frequencies caused by amplifier input capacitance). When a DC current is applied, however, the spectrum shows an excess noise power that scales approximately as $1/f$.

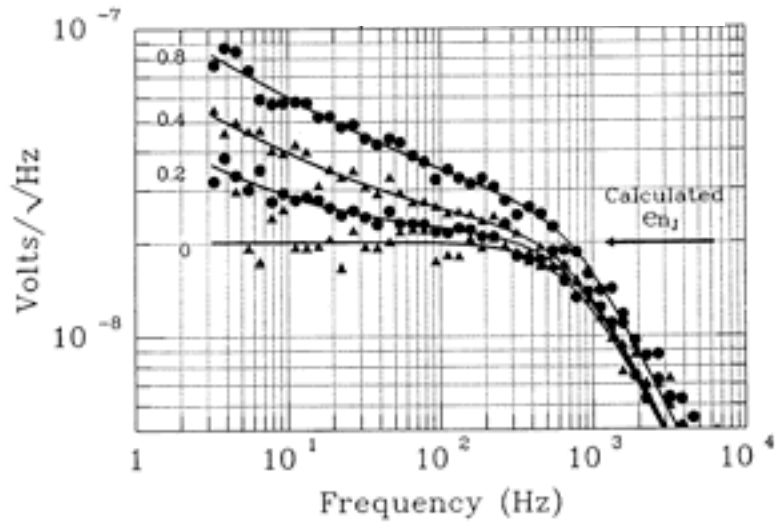


FIGURE 1. Noise spectra of a 250 nm thick implanted silicon thermistor at various bias currents. Currents are shown in nA. The calculated Johnson noise for the zero-bias resistance is indicated.

The observed excess noise is found to be a complicated function of the bias current and temperature. However, if the observed voltage noise is corrected for the voltage-current nonlinearity and divided by the bias current to give equivalent $\Delta R/R$ fluctuations, these fluctuations are found to be a function only of the resistivity for a given doping density. This is shown in Fig. 2a, where we have interpreted the electrical nonlinearity as a hot electron effect [4-6], so that a given resistivity corresponds to an electron temperature. Any combination of lattice temperature and bias that results in the same resistivity gives the same $\Delta R/R$ fluctuations. The relation shows a strong curvature if plotted against log resistivity instead of the inferred electron temperature.

Excess noise of this sort is often produced by problems with the contacts to the thermistor, which in this case are degenerately doped bars along opposite edges of the

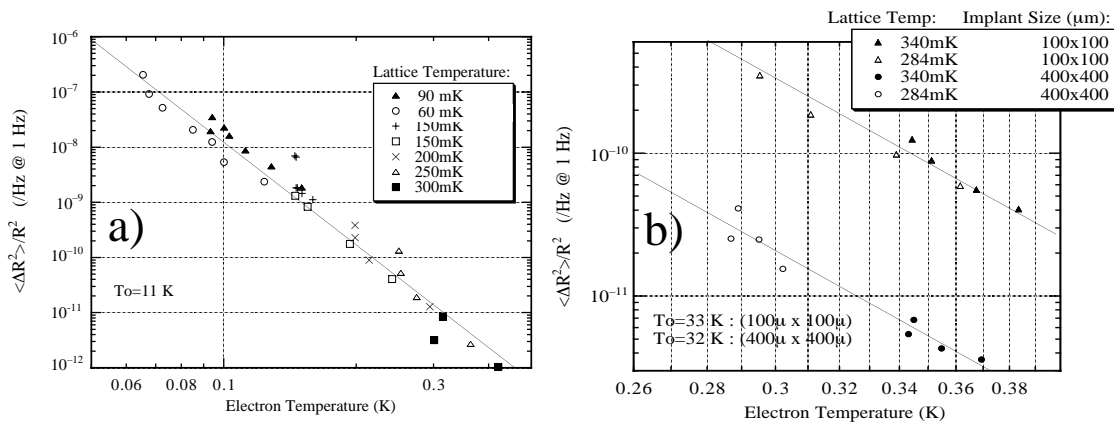


FIGURE 2. a) Shows that the resistance fluctuations depend only on the resistivity ("electron temperature"), independent of the combination of lattice temperature and bias used to achieve it. b) Shows that the fluctuations scale as $1/\text{area}$, as expected for an intrinsic effect. Lines are 16x apart.

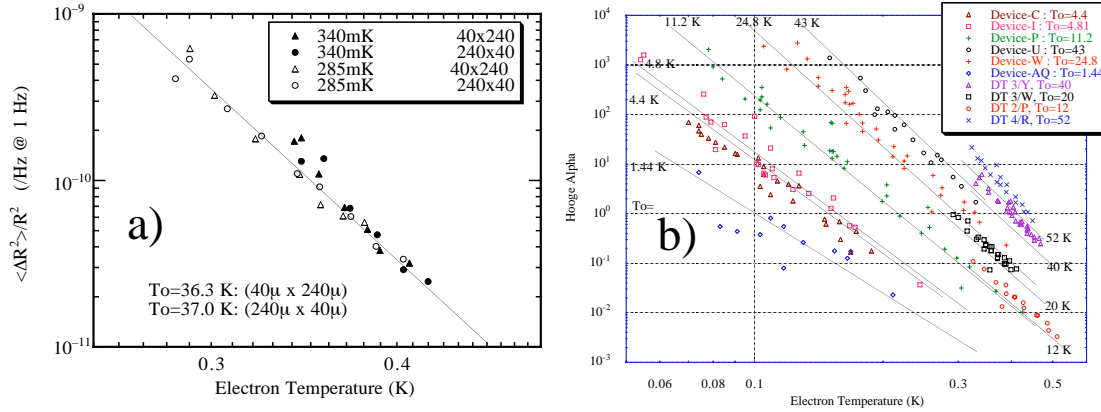


FIGURE 3. a) Shows lack of dependence on contact geometry. b) Dependence of $1/f$ noise parameter on doping density (T_0) and resistivity ("electron temperature"). Taken from reference [7].

rectangular thermistor implant, which are in turn contacted by sputtered aluminum connections at the top surface. However, the results in Figures 2b and 3a give us confidence that we are observing an intrinsic effect in the thermistor. The fractional resistance fluctuations scale as the square root of the size, as is expected for any effect that is intrinsic to the thermistor and statistically independent in different parts of it, and they are the same independent of the geometry of the implant and its contacts.

The $1/f$ fluctuations show a strong temperature dependence, increasing as about T^{-7} as the temperature is decreased, with the power-law exponent a weakly-decreasing function of doping density, which is represented by T_0 in the approximation $R = R_0 \exp(T_0 / T)^{1/2}$. The amplitude of the fluctuations also decreases with increasing doping density. Overall, the temperature and doping density dependence can be fit reasonably well by:

$$\alpha_H = \exp\left(-2.6 + 2.8 \log(T_0) + 2.1 \log(T_0)^2\right) \left(\frac{T_c}{0.15}\right)^{-(5.2+1.8 \log(T_0))}, \text{ where } \left\langle \left(\frac{\Delta R}{R}\right)^2 \right\rangle \equiv \frac{\alpha_H}{Nf},$$

defining α_H as the standard Hooge- α $1/f$ parameter, and N is the total number of charge carriers in the device, which is taken to be $3 \times 10^{18} \text{ cm}^{-3}$ times the implanted volume [7].

IMPACT OF 1/F NOISE ON RESOLUTION

Figure 4 in paper [3] in these proceedings shows the measured noise spectrum of a complete detector that is one of the pixels in an array prepared for the XRS experiment on Astro-E. It also shows calculated contributions from all the known noise sources in the detector, including the predicted thermometer $1/f$ noise from the characterization of the standard implants shown above. The total predicted noise is an excellent fit to the observed spectrum above about 20 Hz. The $1/f$ noise dominates over most of the frequency range where the signal to noise ratio is highest, and it therefore has a significant impact on the energy resolution. In this model, which agrees very well with the observed resolution, removing the $1/f$ noise term would improve the resolution by about 40%.

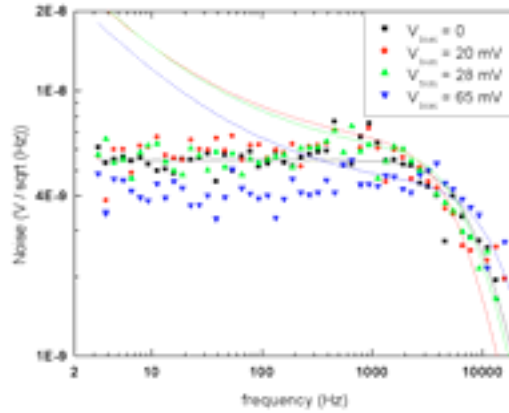


FIGURE 4. Measured noise spectra for 1500 nm thick implants. Solid lines are predicted noise.

THICK IMPLANTS

The characterization of the noise shown above is quite consistent, and similar results are obtained on thermistors fabricated by somewhat different recipes in at least two other laboratories. However, all of these thermistors have approximately the same thickness, which is determined by the ion energies available from the most common industrial implanters. The very steep temperature dependence of the observed $1/f$ noise led us to suspect that it might be a 2-d effect, since the predicted size of the percolation networks is approaching the 250 nm thickness of the standard implants at the temperatures of interest, and is increasing exponentially as the temperature is reduced. As a result, we have tried fabricating 1500 nm-thick implants using methods described in [2].

Noise measurements on the new devices are shown in Fig. 4. The solid lines are the predicted noise using the empirical function derived for the thin implants, scaled to the same implant *volume*. It is apparent that there is no measurable $1/f$ noise, despite the large values predicted. The white noise levels are consistent with predictions of the hot-electron model when transduced thermal fluctuations between the electrons and lattice are taken into account [6]. The $1/f$ contribution to the total noise should be negligible with these thermometers. All other parameters, including electron-phonon thermal conductivity, ρ_0 , specific heat, and even the rise above the $\rho = \rho_0 \exp(T_0/T)^{1/2}$ relation at low temperatures, seem to be almost identical to those for standard thermistors of the same T_0 . This should result in an appreciable resolution improvement for detectors employing implanted silicon thermometers.

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