Transient Phenomena during the Self-Heating of Silicon Devices Operating at Low Temperatures

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In spite of the several experimental findings regarding the cryogenic self-heating of Si devices [1-6], little effort, if any, has been expended in order to understand the actual origin of the measured temperature rise and the observed transients. The transient response to a voltage step was used as a monitor for self-heating [2-4], regardless of the appropriateness of the assumptions on which this technique is based: thermal transients were assumed to be the slowest processes during the relaxation of the sample; thus the slow variation of the current was ascribed to the heating of the devices. However, the thermal time constant must decrease exponentially at very low temperatures due to its direct dependence on the silicon's specific heat, thus leading to faster thermal transients. On the other hand, the relaxation of the depletion region must occur at a slower rate because of the freezing-out of carriers in the quasi-neutral region of the sample, which leads to an increase in the electrical relaxation times.

The aim of this work is to investigate the appropriateness of the transient response method to measure the self-heating at low temperatures, as well as to investigate the region of dominance of several processes leading to such transient. To achieve this goal we estimate several electrical time constants for several mechanisms that can be responsible for the relaxation of the depletion region and/or for ionizing dopants at very low temperatures. The mechanisms considered in this work are the dielectric relaxation, the field-assisted thermal ionization (Poole-Frenkel) and the quantum-mechanical tunneling. The electrical time constants estimated for a typical uncompensated n-type silicon die were compared to its thermal time constant calculated for the 4.2 K<T<300 K range; the results are shown in Fig. 1.

Many interesting facts can be observed in Fig. 1.a) for temperatures around 300 K. The limiting process for the relaxation of the depletion region is simply the dielectric one. It is the longest of the electrical time constants. The tunneling process can be much slower for electric fields lower than 10^5 V/cm; however, it is unimportant as the relaxation by pure thermal ionization (zero-field Poole-Frenkel) is much faster. So that, the latter is the dominant impurity ionization process and is much slower than the dielectric one. A slight difference can be observed when the impurity concentration is incremented by 5 orders of magnitude, as shown in Fig. 1.b). In this case, the dielectric time seems to be shorter than the pure thermal ionization time constant. It then suggests that the limiting process is the ionization of impurities. For both extreme doping concentrations, the thermal time constant is from 6 to 10 orders of magnitude longer than any other; hence, the heat transfer at 300K is much slower than the relaxation of the depletion region.

As the temperature decreases, all the electrical time constants increase, while the thermal one decreases monotonically. No qualitative change is observed from 300 K to around 100 K; the heat transfer is still the slowest process. However, for temperatures below 50 K and low electric fields, no matter what the doping concentration is and which process limits the formation of the depletion region, the thermal time constant is of the same order of magnitude as the electrical time constants. According to Fig. 1, the thermal time constant may even be the shortest under deep cryogenic conditions, below 30K.

Acknowledgements

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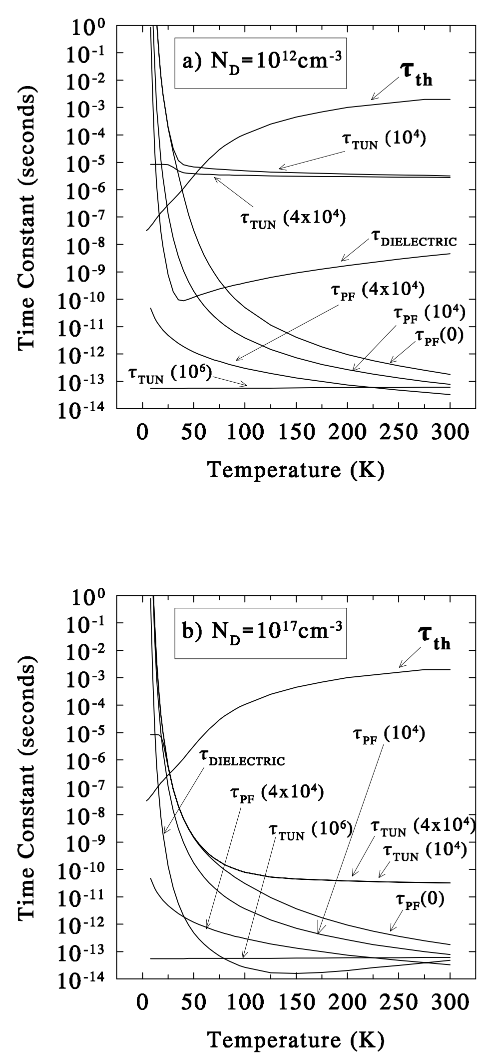

Figure 1: The thermal and several electrical time constants as a function of temperature, for a) $N_D=10^{12}$ cm^{-3}, and b) $N_D=10^{17}$ cm^{-3}. The value of the electric field is indicated in parentheses for the Poole-Frenkel and Tunneling mechanisms.