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Radiation effects on dielectric losses of Au-doped silicon

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Abstract

Effects of electron and neutron irradiation on dielectric properties of Au-doped silicon are examined as a function of the frequency between 1 kHz and 150 GHz. The studies compare the Au-doped Si with a high resisitivity (HR) pure Si in the as-received state and after electron irradiation. The obtained data for both materials show that electron irradiation and neutron irradiation do not cause degradation of the dielectric loss behaviour, but even improve it. This beneficial effect already observed earlier in pure silicon is also observed in Au-doped silicon. Loss data obtained in-beam under electron irradiation are also reported.

1. Introduction

In the latest years special interest has been given to the study of homopolar materials for high frequency applications, mainly CVD diamond and high resistivity (HS) silicon due to their expected low intrinsic loss tangent and high thermal conductivity [1]. Experimental evidence of low losses of HR-Si at 15 and 145 GHz was later confirmed [2,3]. It was shown in Ref. [3] that the loss tangent, measured in HR-Si, is related to the residual concentration of free charge carriers in the material. However it was also observed that these low dielectric losses exhibit a very strong increase in the loss tangent under X-ray irradiation even at small dose rates [2]. Such sensitivity to ionizing radiation, associated with the generation of electron-hole pairs and to the very long lifetime of these carriers, was a severe handicap for the use of silicon at high power gyrotrons. Subsequent work showed that this effect could be drastically reduced by a previous irradiation with high energy electrons, which induce displacement of the atoms in the lattice [4]. In fact, following an electron irradiation up to a dose of 10^{-5} dpa, reductions by more than four orders of magnitude were measured in the loss tangent at 15 GHz under ionizing irradiation. Furthermore, this effect was accompanied by a permanent reduction of the losses by a factor of 50, attaining loss tangents at room temperature as low as 3×10^{-5} at 15 GHz and $(1 \pm 1) \times 10^{-5}$ at 145 GHz. Both effects have been associated with the creation of permanent defects by displacement damage. These defects are thought to act as recombination centres, which drastically reduce the carrier lifetime, the free carrier concentration and hence the loss tangent. The defect responsible for the main effect has not yet been identified. It should have an energy level near midgap since such defects are the most effective in reducing the carrier lifetime [5,6]

Taking these radiation effects into account, the doping of HR-Si with gold was proposed to induce a similar reduction of losses [7]. This idea has recently been put experimentally to evidence [8]. Values as low as $(3 \pm 2) \times 10^{-6}$ at 145 GHz and room temperature have been obtained in Au-doped silicon, demonstrating a promising ultra-low-loss behaviour for fusion applications. Preliminary data under X-rays show major improvements in the radiation sensitivities by the doping [9]. In the present work, the effect of both displacement and ionizing radiation on the dielectric properties of Au-doped HR silicon are systematically investigated, and the results are compared with those obtained in pure material. The permanent radiation effects are also characterized including dielectric properties measurements over a wide frequency range and as a function of temperature, at microwave and millimeter wave frequencies.

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2. Experimental

The HR-Si samples used in this work were obtained from Wacker (Burghausen, Germany) in single crystalline form and grown by the floating-zone method. Before Au-doping the dc resistivity was determined to be 150 Ωm, and the number of extrinsic carriers amounts to 10^{17} m^{-3} [3]. Conductivity was n-type with phosphorous as the major active impurity. From a large block, disc shaped samples were cut with a diameter of 30 mm and an axis oriented parallel to the (1 1 1) direction. The surfaces were polished with a BN suspension to obtain flat surfaces. The materials were doped with Au at a level of around 10^{22} m^{-3} as those samples used in Ref. [8]. After Au-doping conductivity is p-type and resistivity values around 1000 Ωm are obtained [8].

The effect of displacement damage was studied along two alternative routes: the first way was to irradiate a sample with neutrons at pool temperature (around 350 K) up to a fluence of 10^{20} n/m^2 (around 10^{-5} dpa) at the GKSS reactor facility (Geesthacht, D). The dielectric properties of the material, as well as its sensitivity to ionizing radiation, were measured after the irradiation. The second way was to irradiate a sample with 1.8 MeV electrons from a van de Graaff accelerator. In this case the dielectric properties were determined both during and after the irradiation.

Measurement of dielectric properties were performed between 1 kHz and 145 GHz by using three different systems. The commercial system DPMS-1000 (from Japan EM) was used for measurements at frequencies between 1 kHz and 100 MHz. Such system is based in a resonant circuit including a parallel plates capacitor in which the sample is placed. The measuring method was the so-called half varying gap method [10]. Data at 15 GHz were obtained with a resonant cavity-based system as described in Ref. [11]. A Fabry-Perot resonator was used for studies at 145 GHz [12]. The resonant techniques are based on the comparison between the resonance curves with and without a sample inside the resonator.

The measurements at 15 GHz under electron irradiation were performed by installing a resonant cavity at the end line of the van de Graaff accelerator as described in Ref. [13]. Changes in the loss tangent as low as 3×10^{-6} can be detected with this system. In this case, it is important to notice that the dose rate on the material varies along the radius (by around 20%) as well as along the thickness of the sample, giving rise to a relatively large uncertainty in the absolute determination of dose rate.

3. Experimental results

The room temperature values of the loss tangent are summarised in Fig. 1 as a function of frequency for Au-doped silicon in the as-received state, after electron and neutron irradiation. Dielectric properties for as-received and for electron irradiated HR-pure silicon material are also included for comparison. It is observed for all the samples that losses strongly decrease with frequency over the entire range. The graph also shows that Au-doping is, as expected, an effective way to reduce the dielectric losses of HR-silicon. These results confirm those obtained in Ref. [8]. The reduction is less pronounced than in pure silicon after electron irradiation. In this case a reduction of the loss tangent by a factor of 30 is measured after an irradiation up to 10^{-5} dpa, in agreement with results presented in Ref. [5]. Further reductions are obtained in Au-doped samples subjected to electron or neutron irradiation. It is also observed that the reduction induced in the Au-doped sample by a neutron irradiation up to a dose around 10^{-5} dpa is very similar to that induced by an electron irradiation up to a similar dose. This indicates that the efficiency of both radiation sources is similar for permanent loss reductions in this material.

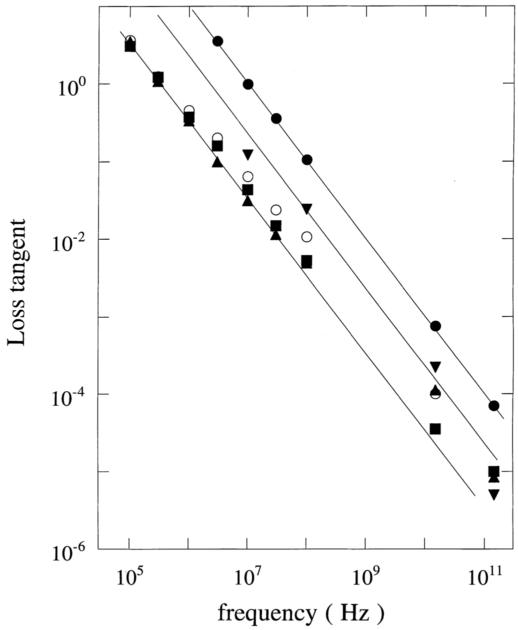

Fig. 1. Loss tangent at room temperature plotted over frequency for (●) HR silicon, (■) HR silicon after electron irradiation up to 10^{-5} dpa, (▼) Au-doped silicon, (○) Au-doped silicon after electron irradiation up to 5 10^{-6} dpa, and (▲) Au-doped silicon after neutron irradiation up to 10^{-5} dpa.

Fig. 2 shows the temperature dependence of dielectric properties for the different specimens at two different frequencies, 15 and 145 GHz. For the pure silicon these curves show a local minimum above room temperature (around 330 K). At higher temperatures, losses increase exponentially due to the thermal excitation of electron

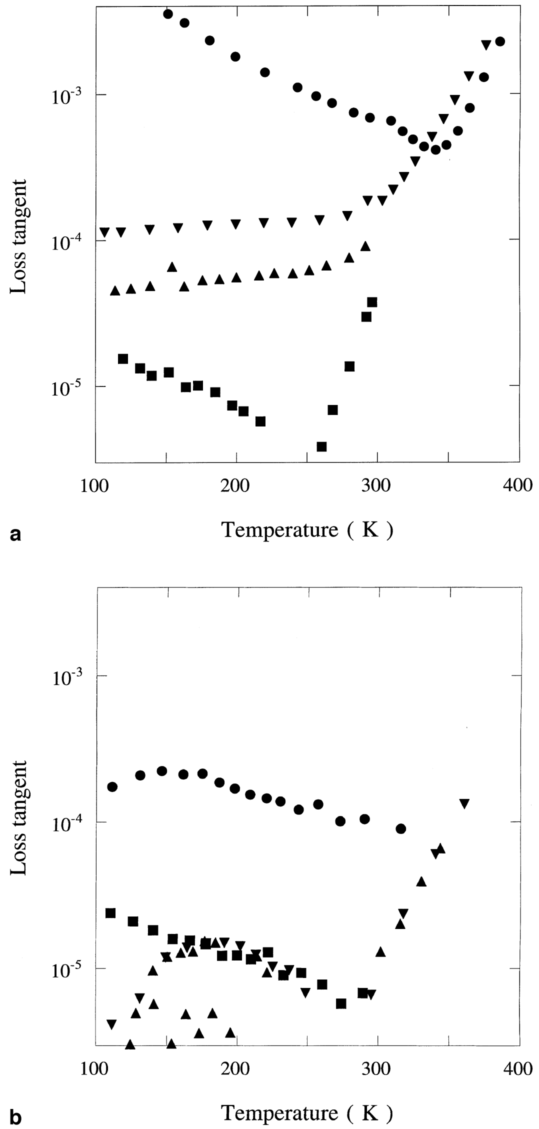

Fig. 2. Temperature dependence of loss tangent at 15 GHz (a) and 145 GHz (b) in (●) HR silicon, (■) HR silicon after electron irradiation up to 10^{-5} dpa, (▼) Au-doped silicon and (▲) Au-doped silicon after neutron irradiation up to 10^{-5} dpa.

hole pairs. At lower temperatures, the loss curve follows the temperature dependence of the mobility of the extrinsic charge carriers. The effect of Au doping as well as of electron or neutron irradiation results in a strong decrease of the losses. This is due to the decrease of the low temperature contribution, lowering the temperature at which the thermal generation of electron-hole pairs is dominant. The comparison of HR pure silicon before and after the electron irradiation shows that the shape of the curve is similar in both cases, although the loss level and the temperature of the minimum are different. On the other hand, it is observed that the curve shape in the low temperature range is different for the Au doped samples. In these samples, the loss curve is more (15 GHz) or less (145 GHz) flattened. This trend is even more pronounced in the Au-doped neutron-irradiated material.

On the other hand, dielectric losses of Au-doped silicon specimens, both as-received as well as neutron irradiated, were also measured at 15 GHz under electron irradiation. It was found that the loss tangent increases during the irradiation. The measured dielectric losses followed a linear relationship with the dose rate, R:

$$\tan\delta = \tan\delta_0 + m\,\mathrm{R},$$

where $\tan\delta_0$ the initial loss tangent and m a function of the total dose, respectively. The same behaviour was found in pure silicon [6]. Therefore, the sensitivity to ionizing radiation is characterized by the factor m. The measured value m for the different Au-doped silicon specimens is compared to that calculated for pure silicon in Fig. 3. It is observed that m decrease several orders of magnitude with the accumulated dose. Au-doped silicon manifests initially a much smaller sensitivity to ionizing radiation than HR silicon. In contrast to HR silicon, no change in m with increasing dose is measured at low doses. Only after a dose of around 10^{-7} dpa, the m factor begins to decrease, coming to a behaviour very similar to HR silicon after a dose around 10^{-6} dpa. Neutron irradiated Au-doped silicon shows a much lower m factor although the total neutron dose is only slightly higher than the electron dose. This result suggests, at least from the point of view of sensitivity to ionizing irradiation, that the neutron and electron irradiation are not equivalent, being the first one more effective.

4. Discussion

Results obtained in this work as well as those reported in Refs. [2–6,8] may be explained in terms of conductivity by free carriers which give rise to dielectric losses inversely proportional to the frequency. Lines representing the law $\tan\delta \sim f^{-1}$ are plotted in Fig. 1 together with experimental results. A very good agreement between experimental data and the theory is shown for pure silicon both as received and after electron irradiation. This is also the case for Au-doped silicon as described in Ref. [8]. The neutron irradiated material however shows a f^{-1} law only at low frequency. Above 10 MHz, a mismatch exists between measured data and the theoretical law. Such a mismatch is also evidenced in the electron-irradiated Au-doped specimen. More experiments are now under progress to clarify the origin of this deviation from f^{-1} dependence.

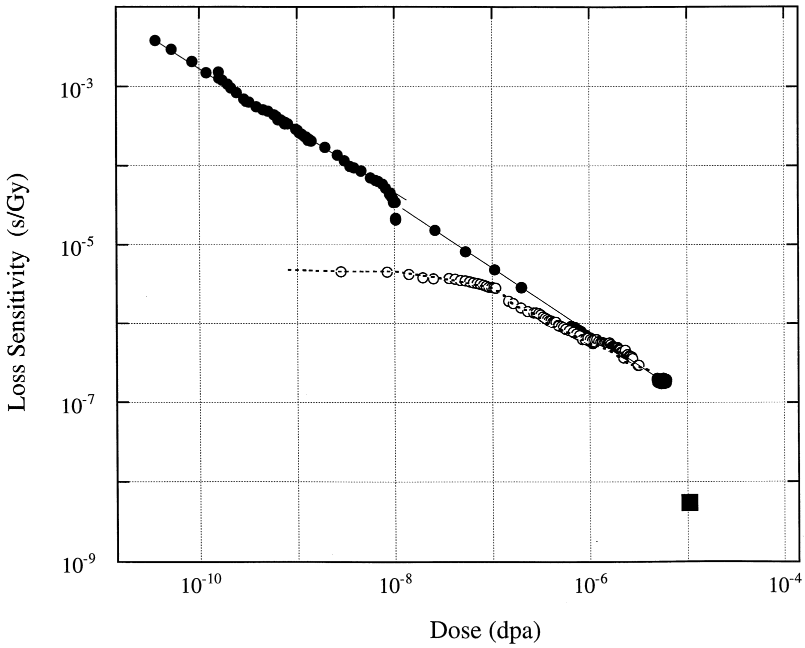

Fig. 3. Sensitivity to ionizing radiation as a function of electron dose in (●) HR silicon, (○) Au-doped silicon. For comparison it has been included the data obtained for Au-doped silicon after neutron irradiation up to 10^{-5} dpa are included (■).

The reduction of loss tangent by electron irradiation was explained in Ref. [6] by means of a reduced carrier lifetime caused by a structural defect created by the irradiation. A similar mechanism may explain the effect produced by Au-doping since Au gives rise to the presence of recombination centers with energy levels near the middle of the gap [14].

The reduced carrier lifetime can also explain the decrease of the loss values measured as a function of temperature and the decrease of the temperature at which the contribution from the thermal excitation to the loss tangent becomes predominant. In the case of Au-doped material, this factor cannot explain the change in the slope of the curves observed in the low temperature region. The only explanation so far is to assume that as a consequence of Au-doing the predominant extrinsic charge carriers are associated with a different defect centre with a different activation energy.

Finally, the observed decrease of the sensitivity to ionizing radiation can also be explained by the reduced lifetime. In a previous work [2] it was shown that m is directly proportional to the charge carriers lifetime. So it is possible to calculate that lifetime changes from about 1 ms for the HR pure silicon to about 1 μs for the Au-doped specimen and about 1 ns for the electron or neutron irradiated ones. From the engineering point of view, these results indicate that the sensitivity to ionizing radiation of silicon is no longer a problem for fusion applications, because the expected dose rates are lower than 50 Gy/s [15]. Anyhow, at this point it is not clearly understood why the decrease of m factor goes over several orders of magnitude whereas the permanent reduction reaches only of a factor of around 30.

5. Conclusions

The effects of electron and neutron irradiation on Au doped silicon have been studied. The irradiated materials show a decrease of losses with respect to the as received material. The in-beam effects are also lower after Au-doping compared to the pure material, but this reduction is accentuated in the neutron irradiated material in which a reduction of six orders of magnitude is observed for the sensitivity to ionizing radiation.. From the obtained results it is concluded that Au-doped silicon should be considered as a promising candidate to be used as high power rf-windows for future fusion machines not only at the output of the high power gyrotron but also at the input of the torus.

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