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# Dependence of carrier lifetime in germanium on resisitivity and carrier injection level

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The dependence of carrier lifetime on resistivity and carrier injection level in germanium crystals is studied using microwave probing of optically excited samples. Bulk lifetimes in the range between 30 ns and 500 $\mu$s are measured. The carrier lifetime decreases with decreasing resistivity and increases with increasing excitation level. Possible mechanisms are discussed and it is shown that the carrier recombination transients are driven by a system of recombination and trapping centers. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2358967]

The direct measurement of carrier lifetime is a powerful tool to evaluate the quality of semiconductor substrates. The dependence of carrier lifetime in Ge on metallic impurities, on temperature, and on material resistivity was intensively studied during the 1950s and 1960s, e.g., Refs. 1–4. It was shown that in low and moderately doped materials, the carrier lifetime can be described well by the Shockley-Read-Hall (SRH) model.[1,2] In addition, in heavily doped Ge, Auger recombination has an important impact on the lifetime.[5–7] The present letter focuses on the influence of resistivity and excitation level on the carrier lifetime in Ge.

Czochralski (Cz) and float zone (FZ) Ge substrates from different sources and with different dopants and resistivities are studied using pulsed infrared excitation in combination with a high spatial resolution microwave (MW) probe.

Excess carrier decay transients are examined by combining MW reflection (MWR) and absorption (MWA) probings of pulsed excited area of the sample.[8] The MW probing is carried out by using a slit of 120 $\mu$m for MWR (at 21 GHz) and 500 $\mu$m for MWA (at 10 GHz) and a coaxial needle-tip antenna for MWR in order to obtain a high spatial resolution. Excess carriers are generated by lasers with 1062 and 1064 nm wavelengths and by using pulses of 700 ps and 10 ns. The excitation wavelength is varied by using harmonics generation, i.e., 1064 and 532 nm wavelengths are used. The variation of the excess carrier decay is examined by MWR and MWA as a function of the excitation level and wavelength.[8]

An influence of the surface recombination on the measured lifetime cannot be avoided even in passivated samples. An initial fast component can be observed in the carrier decays and can be attributed to a transitional process caused by surface recombination. Due to the sharp depth-inhomogeneous initial generated excess carrier profile related to the absorption coefficient of $1.5\times10^4$ cm$^{-1}$ at 1064 nm,[9] a decrease of the amplitude of the main decay mode[8] is observed when comparing etched samples with passivated ones. Also, the asymptotic lifetime differs in passivated and etched samples due to the difference in surface recombination velocity $s$ which is estimated to be larger than $10^3$ cm/s for bare Ge surfaces. Surface recombination has a clear influence on the carrier decay lifetime up to moderately doped material. The effective lifetime $\tau_{\text{eff}}$ of the main decay mode is the result of a bulk ($\tau_b$) and a surface component and can be written as

$$\tau_{\text{eff}}=\left[\frac{1}{\tau_b}+\frac{1}{\tau_s+\tau_D}\right]^{-1}, \tag{1}$$

with $\tau_D=d_{\text{eff}}/\pi^2 D$ and $\tau_s=d_{\text{eff}}/s$.

The surface component consists of a contribution from carrier diffusion ($\tau_D$) and from surface recombination ($\tau_s$), determined by the parameters of carrier diffusion ($D$) and surface recombination velocity ($s$). For well passivated material, $\tau_s$ is of the same order of magnitude as $\tau_D$ and $\tau_b$. For thin samples, however, $\tau_s$ plays an important role in the effective lifetime which can be investigated as a function of $d_{\text{eff}}$ for the determination of small $s$ values. The lower the $s$ value is, the steeper the $\tau_{\text{eff}}=f(d_{\text{eff}})$ dependence. The amplitude of the main decay mode, which can clearly be observed in the case of a sharp excitation profile[8] of effective depth $d_{\text{eff}}$, has to be controlled well for an accurate determination of $s$. For bare surfaces and moderately doped material, carrier recombination is dominated by bulk recombination and fast surface recombination and the slope ($\sim 1/s$) of the $\tau_{\text{eff}}$ dependence on $d_{\text{eff}}$ is small.

The effective (asymptotic) lifetime significantly varies with excitation level and resistivity. In high resistivity material, $\tau_{\text{eff}}$ slightly decreases with additional infrared steady-state illumination at the lowest excitation levels. This implies the existence of recombination and trapping centers. In moderately doped material, $\tau_{\text{eff}}$ increases with excitation level when some threshold excitation level is reached. This increase can be explained by a filling effect of the recombination centers,[10] when the excess carrier concentration becomes larger than the number of recombination centers. In 3 $\Omega$ cm $p$-Ge for example, trap filling occurs for an average excess carrier density above $10^{16}$ cm$^{-3}$. The sharp initial profile which is observed suggests that, most probably, surface traps are saturated by the excess carriers.

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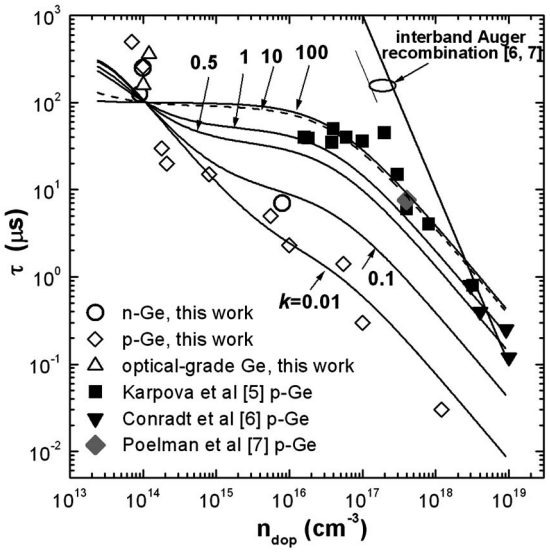


FIG. 1. Variation of the recombination lifetime as a function of dopant concentration. The open symbols represent the lifetime values measured in this work at the lowest possible excitation level: □ for FZ, ◇ for Cz *p*-Ge, and △ for optical-grade Ge. Three data points (open circles, ○) are also given for *n*-type Cz Ge. The closed symbols are published data: ■ from Ref. 5, ▲ from Ref. 6, and ◆ from Ref. 7. The curves illustrate the simulated dependence of lifetime on excitation level with $k=n_{ex}/n_{dop}$ kept constant along each line. Equation (2) is used for the calculations assuming $n_{thr}=4\times10^{16}$ cm$^{-3}$. The two straight lines for high dopant concentrations show the interband Auger recombination lifetime dependence on doping according to Refs. 6 and 7.

In heavily doped material, bulk recombination dominates and the carrier decay transients consist of one component. To obtain a sufficient photoresponse in the high conductivity material, the excess carrier density has to be increased to follow the dopant.

The effective lifetime is to a significant extent determined by bulk recombination. The longest decays of about 2 ms are obtained in FZ high resistivity material. A long asymptotic lifetime is measured also in optical-grade Ge. In the latter material, a clear two-component hyperboliclike decay is, however, inherent, which can be related to carrier trapping and trap filling. In Cz Ge, the effective lifetime decreases from hundreds of microseconds to the nanosecond scale when the resistivity decreases from 35 to 0.01 Ω cm. After correction for surface recombination, the bulk lifetime $\tau_b$ is estimated to be larger than 500 μs in 40 Ω cm *p*-type FZ material, larger than 260 μs in 20–30 Ω cm high purity *n*- and *p*-type Cz materials while it is only 30 ns in 0.01 Ω cm *p*-Ge.

Recombination lifetime $\tau_{eff}$ ($\tau_b$ when possible) values determined in this investigation are generalized and plotted as a function of dopant concentration in Fig. 1 together with data from literature.[5–7] The dopant concentration is determined from Irvin's curves.[9,11] In the present study, the recombination lifetime is determined at the lowest possible excitation levels to fulfill better the low excitation level SRH model conditions. The samples are measured under bias illumination for the low conductivity material to exclude trapping effects. Inevitably, in the heavily doped material, these values are determined at elevated excess carrier density $n_{ex}$.

The measured variation of $\tau_b$ with dopant concentration $n_{dop}$ agrees well up to $n_{dop}\sim10^{16}$ cm$^{-3}$ with the calculated dependence of $\tau_{SRH}$ although assuming, however, deeper traps than those used in Ref. 1. A fixed recombination center concentration can be assumed for doping concentration below $10^{16}$ cm$^{-3}$. The observed further decrease of lifetime for $n_{dop}>10^{16}$ cm$^{-3}$ can be attributed to an increase of the recombination center concentration proportional to the dopant concentration. In this case, the lifetime variation can be approximated well by the phenomenological expression

$$\tau_b = \frac{\tau_{SRH}}{1+(n_{dop}/n_{thr})}, \tag{2}$$

assuming a threshold doping density $n_{thr}$ starting from which the generation of traps by the dopant becomes important.

The lifetime dependence on excitation level and doping calculated with Eq. (2) is illustrated in Fig. 1. For each curve, a constant dimensionless excitation level *k* is assumed given by

$$k = \frac{n_{ex}}{n_0+p_0} \approx \frac{n_{ex}}{n_{dop}}, \tag{3}$$

with $n_0$ and $p_0$ the equilibrium electron and hole densities and $n_{dop}=p_0\gg n_0$ for *p*-type material. This corresponds with a linear increase of the excess carrier density $n_{ex}$ with dopant concentration $n_{dop}$ for each simulated curve. A threshold doping density of $n_{thr}=4\times10^{16}$ cm$^{-3}$ is assumed, and *k* is varied from 0.01 to 100 to evaluate the effect of excitation level on carrier lifetime. For the calculations which are performed for *p*-type Ge, a near midgap trap energy $E_R$ of 0.3 eV is assumed. In this case, a good agreement with the experimental results at low and high excitation levels is obtained assuming that for electrons in *p*-type Ge, the product of the trap capture cross section $\sigma_n$ and the trap density $N_R$ is 0.1. On some of the moderately doped materials deep level transient spectroscopy analyses were performed revealing no deep levels in the material, so that the concentration of traps should be well below $10^{12}$ cm$^{-3}$, suggesting a capture cross section above $10^{-13}$ cm$^2$. The origin and nature of the recombination centers, related to the dopant, are at this stage not clarified.

For dopant concentrations above $10^{14}$ cm$^{-3}$, the calculated lifetime increases with increasing *k*. Moreover, the curves for *k* larger than 0.5, corresponding with medium to high excitation levels, cover most of the experimental values published in Refs. 5–7. This suggests that those data were obtained at rather elevated excess carrier densities to induce an observable photoconductivity signal. The apparent increase of lifetime compared to the low excitation case as used in the present study is due to the well-known[10] trap filling effect for higher excitation levels. The peculiarities of trap filling related to substrate or surface traps can only be observed using short excitation pulses. This trap filling effect could therefore not be observed and investigated in the experiments with long excitation pulses used in Refs. 5–7. Figure 1 also shows three data points for *n*-type Cz Ge measured at low excitation. Although there is no fundamental reason why the minority carrier lifetime should be the same for holes as for electrons, the limited available data suggest that the lifetime behavior is similar to that of *p*-type Ge in the range of low and moderate conductivities.

A degenerate carrier plasma should be considered for high excitation levels with $k>10$ and for $n_{dop}>10^{18}$ cm$^{-3}$. In the present calculations, these effects and also the probable nonlinear recombination processes, which are difficult to analyze for sharp excitation profiles, are included within the phenomenological term $(1+n_{dop}/n_{thn})^{-1}$. The instanta-

neous interband Auger recombination lifetime calculated using an Auger coefficient of $10^{-31}$ $cm^6/s$ (Ref. 6) is shown schematically in Fig. 1 by the two straight lines at high dopant concentrations. The calculations suggest that the impact of interband Auger recombination can only be observed for $n_{dop} > 10^{18}$ $cm^{-3}$, which is above the $n_{dop}$ range investigated in the present study. An alternative explanation for the observed lifetime dependence on $n_{dop}$ above $n_{thr}$ could in principle also be trap-assisted Auger processes.[12,13] However, the estimation of the lifetime taking into account these processes is difficult due to the not well-defined trap-Auger coefficients in Ge and will require further analyses.

The observed lifetime variation with doping shown in Fig. 1 and approximated by Eq. (2), is very similar to the one described for Si when averaging data of a wide range of experiments.[14]

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