On the Problem of Fast Ge:Ga Photodetectors

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Abstract: We investigate theoretically the response mechanism in Ge:Ga-photo detectors and conclude that only very thin detector elements with thickness of the order 0.1 *mm* or less obtain reasonably bandwidth of the order of 50 *MHz* and higher.

Key words: THz-detector 118.9 μm wavelength, Ge:Ga-detector, fast response

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1. Introduction

One of the most efficient methods to characterize electronic energy levels in semiconductors is the THz-magneto spectroscopy [1]. Monochromatic THz-radiation with the energy of some *meV* excites electrons between appropriate energy levels. To enforce resonance absorption the energy levels are tuned by application of strong external magnetic fields. In the resonance the radiation energy equals exactly the energy separation of the levels involved. If the states of the electrons are quasi-free states we observe the well known cyclotron resonance. For many materials extremely high magnetic fields in the megagauss regime are necessary to observe resonance absorption. So far only pulsed magnetic fields – the single-turn-coil method and the flux compression – are applicable for this regime. The characteristic pulse parameters for these field generators are in the order of some µsec. Within this time the magnetic field is swept from zero to the maximum field and the optical spectrum – mostly transmission – shows more or less sharp resonances depending on the Q-value of the resonance. To detect this spectrum with the rapid changes an extremely fast detector system is necessary with a bandwidth in the order of 50 *MHz*. Please note that for a realistic response of the detector system it is necessary that the response variable – mostly the detector current – is absolutely independent of the frequency.

One of the strongest lines in the THz-regime is the 118.6 μm-line of the optically pumped methanol laser. The corresponding radiation energy is nearly in resonance with the impurity excitation in Ga-doped Germanium, so that this material can be used to construct a sensitive detector system for this radiation wavelength [2]. For DC-magnetic fields the efficiency of the Ge:Ga-detector has been demonstrated in countless experiments applying lock-in technique at low modulation frequencies [3]. In high-field experiments with short pulse time the detector response exhibits, however, due to the high resistance of the material irregularities.

In the present theoretical study we concentrate completely on the Ge:Ga-detector and how to overcome the limitations of intrinsic scattering and relaxation processes limiting the time response of the system.

2. The Ge:Ga-Detector

2.1 The internal photo-effect in semiconductors

The internal photo-effect in Ge:Ga relies on the ionization of the hole of Ga-acceptor into the valence band of Ge, shown schematically in Fig. 1 [3].

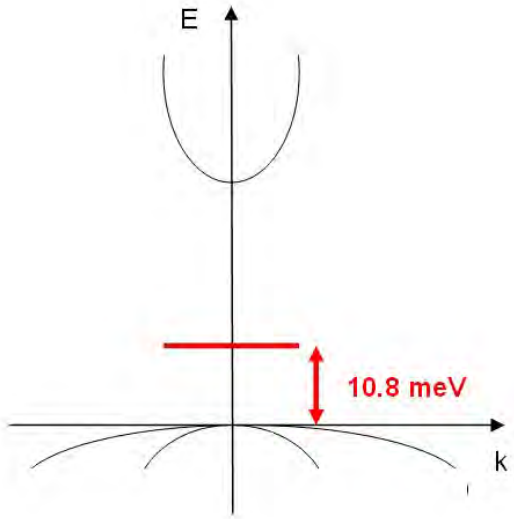

Fig. 1 The Ga-acceptor in Ge has a binding energy of $E_B = 10.8$ meV.

2.2 The arrangement of the detector element in practical experiments

To obtain maximum efficiency in the absorption of the radiation by the active – Ga-doped - part of the Ge-crystal, the element is usually mounted within an integrating sphere, so that by multireflection within the sphere all incident radiation is absorbed, as shown schematically in Fig. 2. We assume that all or a well defined layer of the Ge-crystal is homogenously doped. The crystal faces are contacted by electrical leads of Cu or Au using In-older [3].

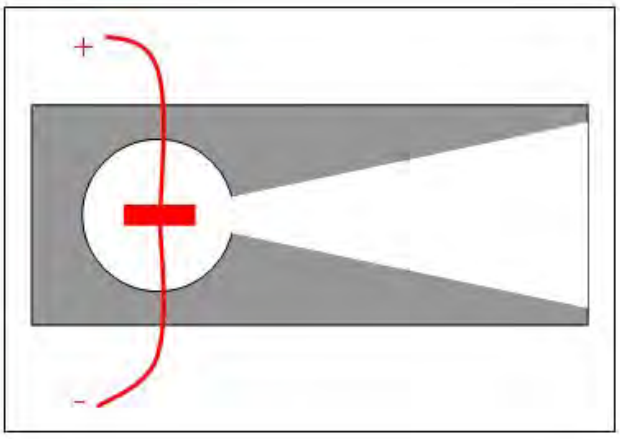

Fig. 2 The detector element is mounted within an integrating sphere so that all incident radiation is absorbed inside the Ga-doped part of the crystal.

2.3 **Generation and Recombination in the Detector**

For the theoretical consideration of the carrier system inside the detector we consider for generality a layered structure of undoped and doped regions as shown in Fig. 3. It is assumed that neither carrier excitation nor carrier recombination can occur inside the undoped layers. Only ordinary scattering determines the drift mobility μ as in any conductor. Also for studying the recombination mechanism we consider an unirradiated part of the doped crystal between x_2 and x_3.

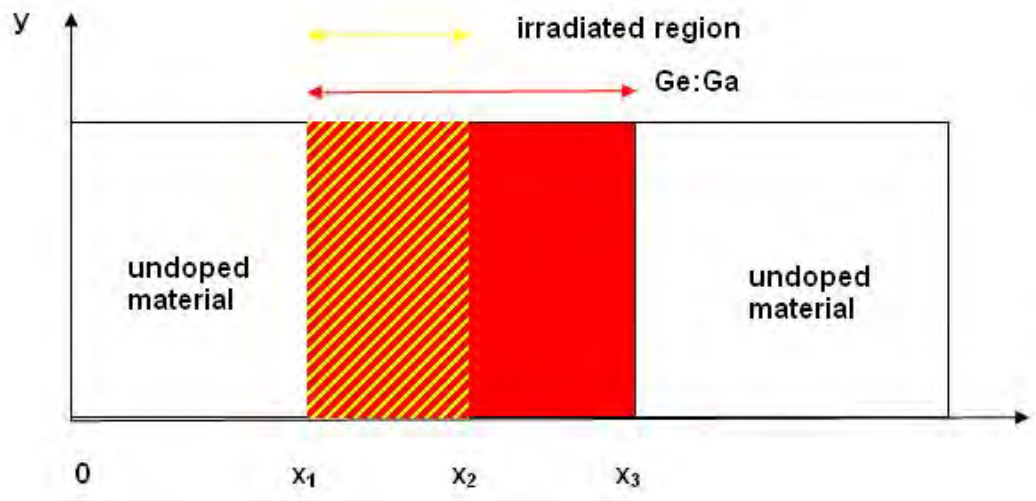

Fig. 3 Schematics of the detector layers

In contrast to the external photo effect where the charge carrier is excited into the vacuum, here the mobile hole is in the valence band and experiences both scattering and recombination into empty impurities resulting in a finite mobility μ as well in a finite life time τ. This is why we have to establish the differential rate equation for the time-dependent local hole concentration $n_h(x,t)$ and the current:J(x,t):

$$J(x,t) = eAvn_h(x,t) \tag{1}$$

in a volume element of thickness dx with a cross section A. Here $n_h(x,t)$ is the hole concentration at position x and time t, and e the elementary charge. The drift velocity v of the charge carriers into the direction of the positive x-axis is considered to be constant in the doped layer. This assumption is correct also long as photo-induced change of the resistance ΔR is small with respect to the background resistance R_0 of the detector element.:

$$\Delta R/R_0 << 1 \tag{2}$$

The terms $eAg_hI(x,t)dx$ and $eA(n_h(x,t)-n_h^0)dx/\tau$ describe the generation of quasi-free holes due to the generation rate g_h, the absorbed radiation power per volume I(x,t), and the recombination time τ, respectively.

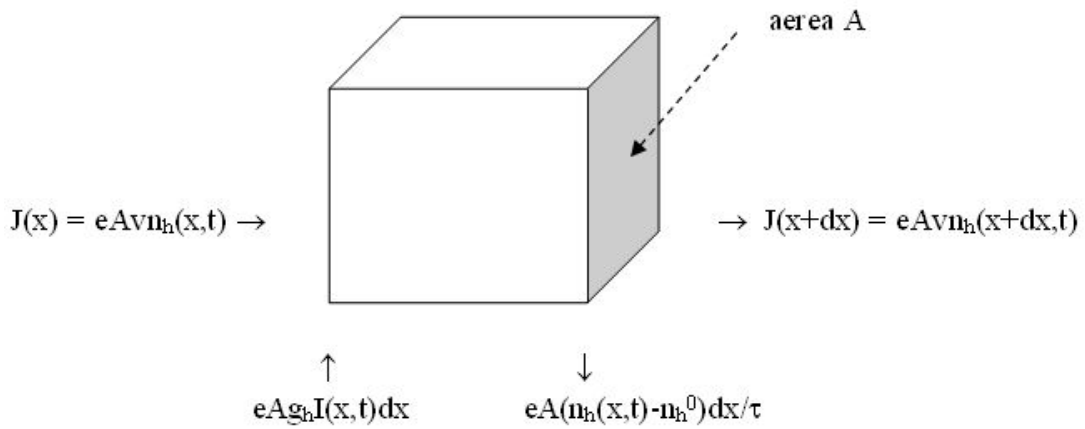

Fig. 4 Schematic of the different contributions to the current in the volume element Adx.

2.4 The rate equation

We obtain the following equation:

$$v dn_h(x,t)/dx = [eAg_h I(x,t) - \{n_h(x,t) - n_h^0\}/\tau] \quad (3)$$

resulting with:

$$dn_h(x,t)/dx = \partial n_h(x,t)/\partial x + 1/v * \partial n_h(x,t)/\partial t \quad (4)$$

in:

$$v\partial n_h(x,t)/\partial x + \partial n_h(x,t)/\partial t = eAg_h I(x,t) - [n_h(x.t) - n_h^0]/\tau \quad (5)$$

This is an inhomogenous linear partial differential equation of first order in x and t.

Considering for the modulated radiation intensity I(x,t) a time dependence of the form $I_\omega(x)e^{i\omega t}$ we recognize that all other time dependent quantities must have the same time dependence. So we can introduce a new quantity independent of time:

$$\Delta n_{h\omega}(x) = [n_h(x,t) - n_h^0]/e^{i\omega t} \quad (6)$$

and can transform equ. 4 into an inhomogenous ordinary differential equation of first order in x:

$$v d\Delta n_{h\omega}(x)/dx = [eAI_\omega(x)g_h - \{1/\tau + i\omega\}\Delta n_{h\omega}(x)] \quad (7)$$

2.5 Solution of the rate equation:

We define now the spatial dependence of the different quantities according to Fig. 3:

$$<x_1, x, x_2> : \; I_\omega(x) = I_\omega \text{ otherwhise } I_\omega(x) = 0 \quad (8)$$

$$<x_1, x , x_3> : \ \tau(x) = \tau \text{ otherwise } \tau(x) = \infty \tag{9}$$

For the different ranges we obtain the following solution:

$$<x_1, x , x_2> : \Delta n_{h\omega}(x)e^{i\omega t} = eAI_{\omega}g_h e^{i\omega t}[1 - e^{-(1/\tau + i\omega)(x-x_1)/v}]*v/(1/\tau + i\omega] \tag{10}$$

$$<x_2, x , x_3> : \Delta n_{h\omega}(x)e^{i\omega t} = eAI_{\omega}g_h e^{i\omega t}[1 - e^{-(1/\tau + i\omega)(x_2-x_1)/v}]*v/(1/\tau + i\omega]*\ldots$$

$$\ldots*e^{-(1/\tau + i\omega)(x-x_2)/v} \tag{11}$$

Please note that the quantity

$$D_{layer} = (x_3-x_1) \tag{12}$$

denotes the thickness of the Ga-doped Ge-layer

$$D_{irradiation} = (x_2-x_1) \tag{13}$$

and the thickness of the irradiated part of the Ga-doped Ge-layer.

We have assumed that for D = 0 holds:

$$\Delta n_{h\omega}(0) = 0 \tag{14}$$

This means that there is no photo contribution from outside the doped layer in the detector crystal.

The quantity $\Delta n_{h\omega}(x)$ is the key quantity for the detector response, because it enters directly into the final response quantity of the detector. In Fig. 5 we have plotted the function $Re\{\Delta n_{h\omega}(x)\}$ creating a charge density wave of the excess carriers in the crystal for parameters close to those for ultra-low compensation as given in [4] .

Generally we observe in the detector crystal strong dispersion caused by travelling-wave effects as well of the recombination of the excited space charge. Only for very thin layers the dispersion is negligible. This can be derived directly from equ. (10) for small values of the exponent. In this case holds:

$$<x_1, x , x+\Delta x> : \Delta n_{h\omega}(x)e^{i\omega t} = eAI_{\omega}g_h*\Delta x/v\, e^{i\omega t} \tag{15}$$

with:

$$\Delta x << |v/(1/\tau + i\omega)| = v\tau/\sqrt{(1+\omega^2\tau^2)} = D_{eff} \tag{16}$$

For $\omega = \omega_0 = 5\times10^7$ *Hz* we obtain $D_{eff} = 0.159$ *mm* as indicated in Fig. 5. As the red curve shows over this thickness the dispersion can be neglected for $\omega = 5\times10^7$ *Hz*.

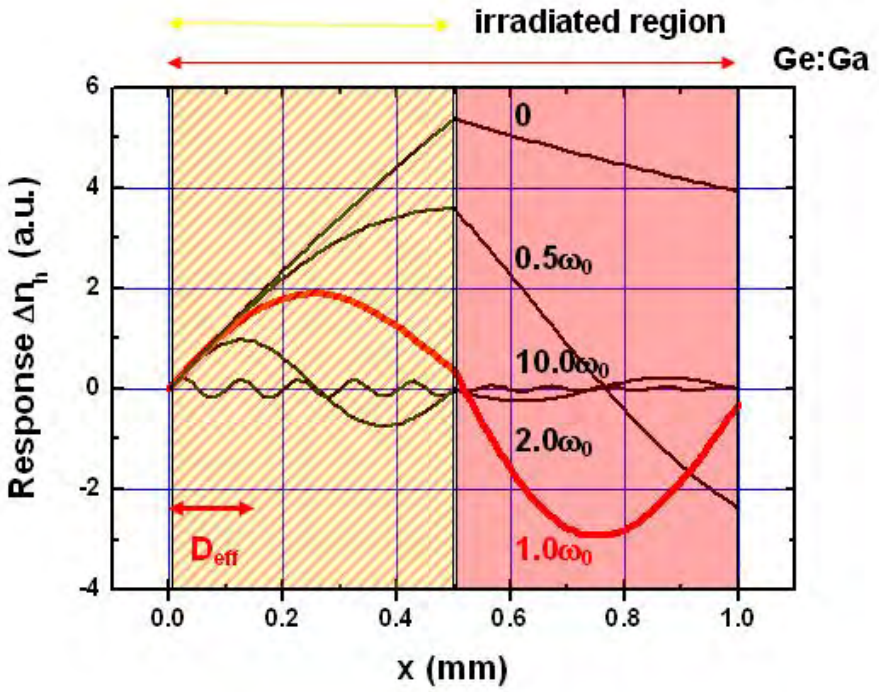

Fig. 5 The real part of the charge density wave of the excited carriers in the detector crystal.The parameters indicate the frequency ω in multiples of $\omega_0=5\times10^7$ *Hz*. The values for the recombination time is: $\tau=2\times10^{-7}$ *sec*. The drift velocity $v=8\times10^6$ *mm/sec* results from an assumed mobility of $\mu= 8\times10^5$ $cm^2/(Vsec)$ and a break-down field for impurity ionization of $E_{break}=1$ *V/cm*.

2.6 Total resistance change of the detector element

To find the actual macroscopic total resistance change of the detector element as a function of the thickness parameters we have to find the radiation induced change in the total resistance of the detector element. We assume that we have irradiated the total of the doped Ge:Ga-layer, so that with equ. (2) we have:

$$R_0 + \Delta R = \int_0^{D_{layer}} dx/[A*(\sigma_0 +\Delta\sigma)] \approx [1 - \int_0^{D_{layer}} dx\Delta\sigma/\sigma_0] *D_{layer}/(A\sigma_0) \quad (17)$$

$$\Delta R_\omega/R_0 = - \int_0^{D_{layer}} dx\Delta n_{h\omega}(x)/(n_0*D_{layer}) \quad (18)$$

Straight forward integration of equ. (18) results in:

$$\Delta R_\omega/R_0 = - \frac{eAI_\omega g_h}{(n_0*D_{layer})} \int_0^{D_{layer}} dx\, [1 - e^{-(1/\tau + i\omega)(x-x_1)/v}]*v/(1/\tau + i\omega) = \ldots \quad (19)$$

$$\ldots - \frac{eAI_\omega g_h}{(n_0*D_{layer})} *\{D_{layer} -[1 - e^{-(1/\tau +i\omega)D_{layer}/v}]*v/(1/\tau + i\omega)\}*v/(1/\tau + i\omega)$$

It should be noted that the total power P_ω of frequency component ω absorbed in an integrating sphere by a homogenously doped detector element of thickness D_{layer} is:

$$P_\omega = I_\omega * D_{layer} \tag{20}$$

assuming that all intensity entering the integrating sphere is absorbed. So normalizing the result of equ. (19) in this way we obtain:

$$\Delta R_\omega/R_0|_{Ptotal=\ const.} = -\underline{eAg_h P_\omega} * \{D_{layer} - [1 - e^{-(1/\tau + i\omega)D_{layer}/v}] * v/(1/\tau + i\omega)\} * v/(1/\tau + i\omega)$$

$$(n_0 * D_{layer}^2) \tag{21}$$

For thick samples with:

$$D_{layer} >> v//(1/\tau + i\omega) \tag{22}$$

We obtain from equ. (21):

$$\Delta R_\omega/R_0|_{Ptotal=\ const.} = \frac{-eAg_h P_\omega v}{(n_0 * D_{layer})} * \frac{1}{(1/\tau + i\omega)} \tag{23}$$

This frequency dependence has been given before by [5].

In Fig. 6 we have plotted the real part of this result as function of the layer thickness D_{layer}:

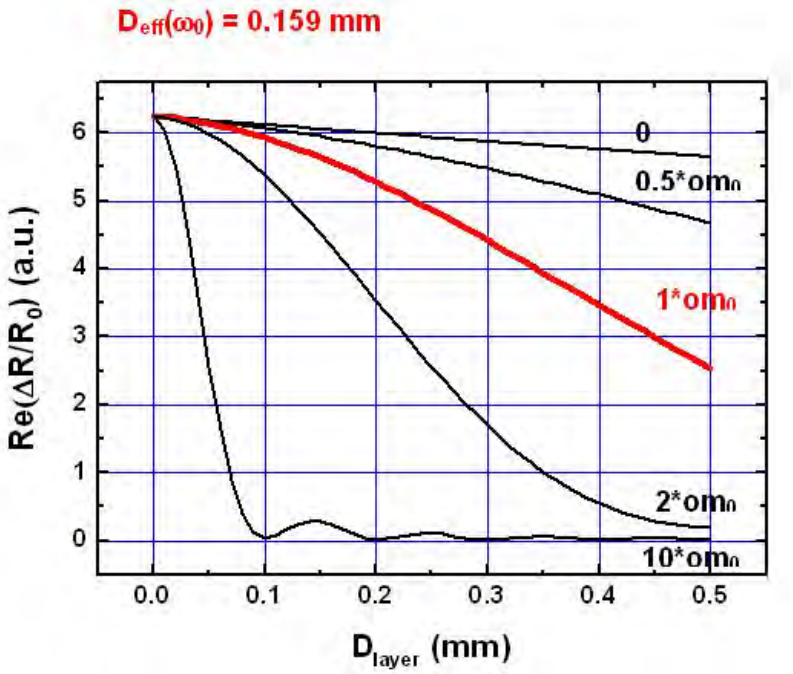

Fig. 6 The real part of the resistance change of the detector element due to irradiation as a function of the thickness D_{layer} off the detector element. The parameters indicate the frequency ω in multiples of $\omega_0 = 5 \times 10^7$ *Hz*. The value for the recombination time is: $\tau = 2 \times 10^{-7}$ *sec*. The drift velocity $v = 8 \times 10^6$ *mm/sec* results from an assumed mobility of $\mu = 8 \times 10^5$ *cm²/(Vsec)* and a break-down field for impurity ionization of $E_{break} = 1$ *V/cm*.

Fig. 6 demonstrates again that the useful thickness range for the detector element is smaller than D_{eff}. This can be visualized directly from equ. (19) for small arguments of the

exponential function, i.d. for $D_{layer} << D_{eff}$. We have to consider in the expansion also terms of second order. For this limit holds:

$$\Delta R_\omega/R_0|_{Ptotal=const} = \frac{-eA\ g_h}{2n_0}*(I_\omega D_{layer}) = \frac{-eA\ g_h}{2n_0}*P_\omega \qquad (24)$$

It is interesting to investigate directly the frequency dependence of $\Delta R_\omega/R_0|_{Ptotal=const}$.

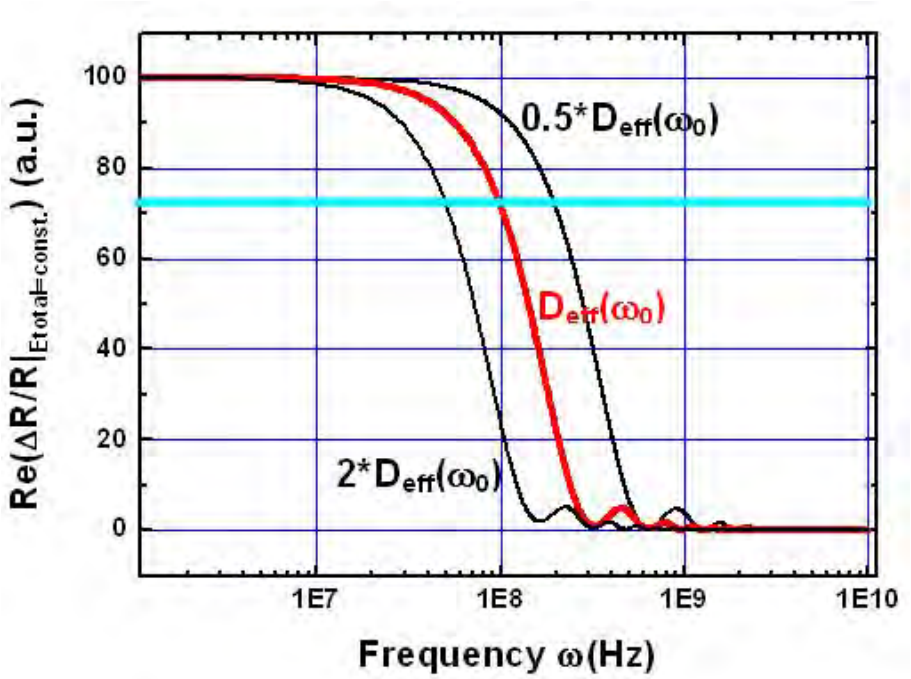

Fig. 7 The response of the detector element with thickness D_{layer} as given by the parameters in the figure. Please note, that $D_{eff}(\omega_0=50\ MHz) = 0.159\ mm$ has been calculated for $\omega_0=50\ MHz$. The horizontal line indicates the 3dB-value. The value for the recombination time is: $\tau=2\times10^{-7}\ sec$. The drift velocity $v=8\times10^6\ mm/sec$ results from an assumed mobility of $\mu= 8\times10^5\ cm^2/(Vsec)$ and a break-down field for impurity ionization of $E_{break}=1\ V/cm$.

Fig. 7 demonstrates that even for $D_{layer} = D_{eff}(\omega=50\ MHz)$ we have a bandwidth of about $\Delta\omega\approx2\omega_0=50\ MHz$ using the 3dB-definition (70.7%). Generally, the thinner the detector layer D_{layer} is, the larger the bandwidth.

2.7 Suggestion for practical realisation of a fast Ge:Ga-detector

The above study has shown that the construction of a fast Ge:Ga.detector with a bandwidth larger than 50 *MHz* can be easily constructed using thin detector layers with $D_{layer} \approx$ (0.1 to 0.2) *mm* as well as high mobility material with ultra low compensation. An increase of the compensation to shorten the recombination time τ as proposed before [6] is contraproductive for our purpose. The need of transparent contact coating for thin detector layers can be avoided by suitable structuring of the surface. We propose the following contact structure as shown in Fig. 8 and Fig. 9 which are easily manufactured by modern evaporation techniques. The structure shown in Fig. 9 has the advantage, that even spurious linear polarization effects are avoided.

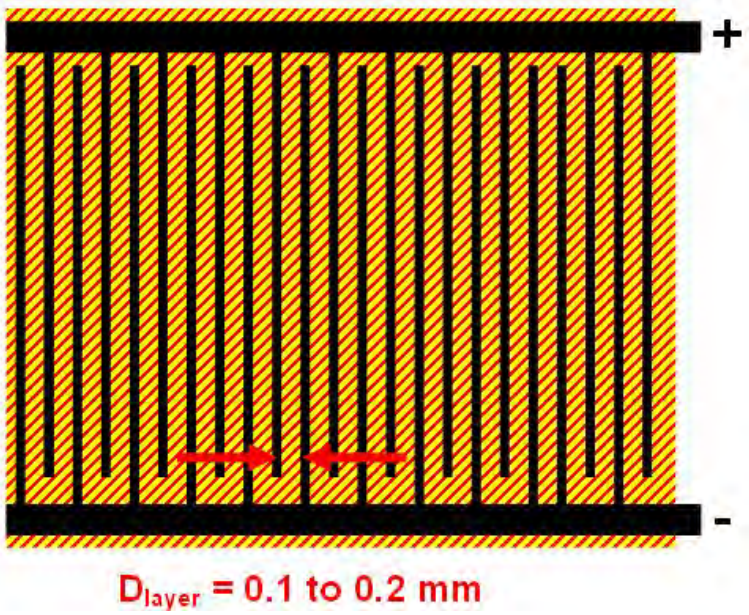

Fig. 8 The Ge:Ga layer of about 0.1 *mm* thickness on undoped Ge is structured by an evaporated contact grid with linear structure. The "layer distance" D_{layer} is in the order of 0.1 to 0.2 *mm*.

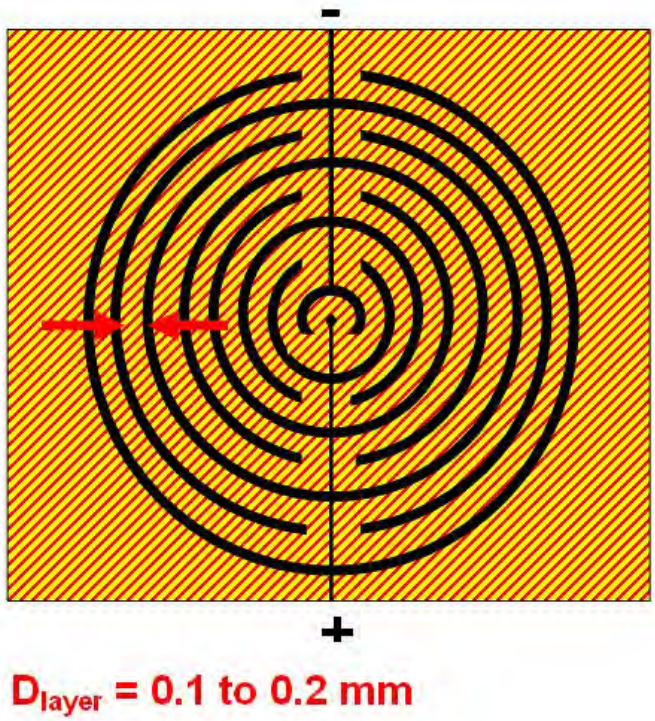

Fig. 9 The Ge:Ga layer of about 0.1 *mm* thickness on undoped Ge is structured by an evaporated contact grid with rotational symmetric structure. The "layer distance" D_{layer} is in the order of 0.1 to 0.2 *mm*.

3. Summary

We have demonstrated that suitable material choice and shaping of the Ge:Ga-detector for 118.9 μm wavelength radiation gives the possibility for extremely wide frequency response well above 50 *MHz*. Low-compensation material of high mobility should be used for very thin detector layers of the order of 0.1 *mm* thickness.

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