11-9

Radiation Detectors by Use of Nonequilibrium Depletion in MIS Structure

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This paper presents a new method for measuring γ-rays and other ionized particles, and also for measuring some parameters of Metal-Insulator-Semiconductor (MIS) structures.

The generation current caused by γ-rays or other particles can be analyzed from one or two of the following measurements: transient capacity C, photo voltage V_{ph} and longitudinal conductivity σ_ℓ under the condition of a nonequilibrium space charge depletion region (NE-SCR) in the MIS structure.

Theoretically, by observing the transient characteristics of C, V_{ph} and σ_ℓ as a function of radiation intensity, volume and surface parameters of the semiconductor such as mobility etc. can be determined. For instance, in case of an initial depletion SCR,

$$C_{ef} = C^{o}_{ef} \left[1 - \frac{(C^{o}_{ef})^2}{C_I} \cdot \frac{2}{\varepsilon_s \cdot \varepsilon_o \cdot p_o} \cdot I^{*} \; . t \right]^{-1/2} , \; I^{*} = K(1-R).I \qquad (1)$$

where C^{o}_{ef} is the small signal capacity of the MIS structure before the field is applied creating depletion in the MIS system, $\varepsilon_o = 8.854 \times 10^{-14}$ F/cm, ε_s = dielectric constant of the semiconductor, p_o = the concentration of free carriers, C_I = capacitance due to the insulator, I = radiation dose rate, K = quantum efficiency, R = reflection constant and t = time.

For analytical study, there are several cases which can be considered. 1) In case of a fully depleted sample, the so called "pinch-condition", the time duration of pinch should be measured and 2) the effective relaxation time t_{SCR} should be measured. 3) In case of a non-fully depleted sample, the small-signal capacitance derivation $(\frac{\partial C_{ef}}{\partial t})$, and other quantities such as $(\frac{\partial V_{ph}}{\partial t})$, $(\frac{\partial \sigma}{\partial t})$ should be measured. In case 3, the following equations hold, where W_o is depth of the SCR before irradiation. (V_{ph} shown in the second equation is the open circuit voltage)

$$\frac{dC_{ef}}{dt} = \frac{(C_{ef})^3}{C_I} \cdot \frac{1}{\varepsilon_s \cdot \varepsilon_o \cdot p_o} \cdot I^* \; ; \quad \frac{dV_{ph}}{dt} = \frac{e.W_o}{\varepsilon_s . \varepsilon_o} \cdot I^* \qquad (2)$$

From such approaches a direct and simple method is presented to: 1) determine the integral doses of various type radiations, i.e. from γ-rays to the near IR using of the silicon MIS system, 2) measure the shape of light pulses, 3) measure the values of quantum yield for several semiconductors, 4) measure free carrier distribution or mobility and 5) measure surface trapped charge.

The above theoretical predictions were examined experimentally and the results showed quite good agreement with the theoretical values. The experiment was performed using γ-radiation and visible light. The sample was a high resistivity Si wafer ($p_o = 2.5 \times 10^{12}$ /cm^3). The frequency used for determination of capacitance was 10^4 Hz. Some of the results are shown in the following table.

Sample No.	t_{SCR}(sec)	Intensity$^{(1)}$ of γ-rays (r/sec)	Calculated Intensity$^{(2)}$ of γ-rays using the theory (r/sec)
1	0.44	2.03	2.2
2	$6\mathrm{x}10^2$	$2.2\mathrm{x}10^{-3}$	$1.8\mathrm{x}10^{-3}$
3	$1.8\mathrm{x}10^3$	$7.1\mathrm{x}10^{-4}$	$6.3\mathrm{x}10^{-4}$

(1) These values were measured by a p-n solid state detector.

(2) In this value, K is assumed to be $0.013 \times 3.8 \times 10^5$.

The theoretical relations were checked experimentally in more detail using visible light ($\lambda = 0.345\mu$). In Fig. 1, we show the dependence of the derivative $(\frac{dC_{ef}}{dt})$ on intensity of light. For the whole range of intensity I, $(\frac{dCef}{dt})$ shows a linear relation in agreement with Eq. (2). The values of intensity, calculated from these data, are in agreement with ones independently measured by a p-n junction solid state detector. The sensitivity of this type of detector is $\sim 10^{-11}$ W/cm^2, which is comparable with ordinary p-n junction detectors. Figure 2 shows a comparison of theoretical photo-voltage curves with experimental ones, measured for the cases of "shunt" (1) and open (2) circuits, as a function of the depth penetration of the non-equilibrium SCR. The depth penetration was calculated from the effective capacitance of the MIS system. Note, that for case (2) we have very large values of V_{ph} ($\sim 10^2$ - $\sim 10^3$V). The variable parameter for case (1) is intensity, I and for case (2) hole density, p_o. Figure 3 shows the values of depletion SCR-depth $W \sim (\frac{2U_s}{\varepsilon_s \cdot \varepsilon_o \cdot e \cdot p_o(x)})$ (where U_s is surface potential, which equals V_{ph} for the open-circuit case), calculated from V_{ph} (circles), C_{ef} (points) and σ_ℓ (threctangles) vs. longitudinal current J. The reasonable coincidence of all data points implies that the main assumptions used by the theory are fulfilled and the MIS sample used was homogeneous. If we measure two relaxation effects simultaneously, we can obtain the depth distribution p_o (x) for the case of constant mobility, or we can obtain the mobility distribution $\mu(x)$ for the case of constant carrier density.

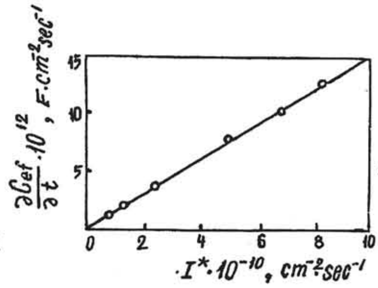

Fig.1

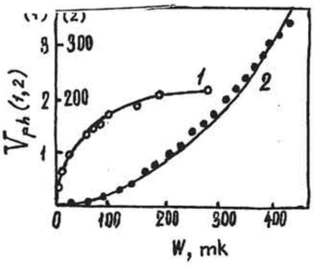

Fig.2

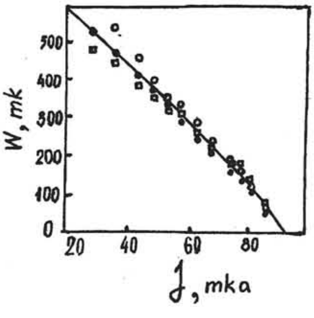

Fig.3

In conclusion, we have demonstrated several advantages for this method. It does not use p-n junctions which are difficult to fabricate for a large number of semiconductors of interest, but employs well developed MIS technology. It enables the use of pure material which has very low recombinational loses and the attraction of low noise properties.