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A LOOK AT THE PHENOMENON OF CHARGE MULTIPLICATION IN SILICON RADIATION DETECTOR WITHIN THE CONCEPT OF DYNAMIC FOCUSSING OF THE ELECTRIC FIELD

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Взгляд на явление мультипликации заряда в кремниевом детекторе в пределах концепции динамической фокусировки электрического поля

Спектры ионов ^{34}S и ^{40}Ar, измеренные кремниевым детектором, были проанализированы в пределах концепции динамической фокусировки электрического поля. Значение величины ионизационной константы b было получено для различных полей. Сделана оценка температуры горячих электронов. Предложен сценарий развития процесса мультипликации, учитывающий роль начальной концентрации электронов и дырок в образовании подсистемы горячих носителей.

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A Look at the Phenomenon of Charge Multiplication in Silicon Radiation Detector Within the Concept of Dynamic Focussing of the Electric Field

The spectra of ^{34}S and ^{40}Ar ions measured with silicon detectors were analyzed within the concept of dynamic focussing of the electric field. The ionization constant b was obtained for different fields. An estimate of temperature of hot electrons was obtained. A reasonable scenario for development of charge multiplication process is suggested, taking into account the influence of initial electron-hole concentration on the formation of hot carriers subsystem.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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The effect of charge multiplication is known since silicon detectors were used for fission fragment and heavy-ion spectrometry [1-5]. The first theoretical treatment associated this phenomenon with tunneling of electrons from front electrode into the depletion layer of the semiconductor [2]. A different concept was developed in [3,6] based on avalanche multiplication due to the dynamic focussing of the electric field by the plasma column created by charged particle. In [6] the mentioned concept was applied to explain the charge multiplication effect of the order of 10^{-4} measured for 5.8 and 7.65 MeV alpha particles, much less than the one measured for heavy ions and fission fragments. The formula for the value of multiplied charge was derived:

$$\frac{\Delta Q}{Q_r}=\frac{AR_0^3}{4Dt_p}\left(\frac{F_m}{b}\right)^3\left(1+\frac{b}{F_m}\right)e^{-b/F_m}\left\{1-\frac{1+\frac{b}{F_m}\frac{r_0(t_p)}{R_0}}{1+\frac{b}{F_m}}exp\left(-\frac{b}{F_m}\left(\frac{r_0(t_p)}{R_0}-1\right)\right)\right\} \quad (1).$$

Here:

ΔQ is the charge multiplication value,

Q_r — the regular charge value (without multiplication),

D — the ambipolar diffusion constant,

R_0 — the initial plasma column radius,

$r_0(t)=(R_0^2+4Dt)^{1/2}$,

$b=1.2316\times10^6$ Volt/cm, $A=0.703\times10^6$ 1/cm — constant from the relation for avalanche ionization coefficient in the conventional form of $\alpha(F)=Aexp(-b/F)$, where F is the electric field,

t_p — the plasma time,

F_m — the value of maximum electric field at the track pole.

Note, that for better agreement with experimental data the authors of [6] have taken the value of R_0 which is about seven times larger than the one reported by Seibt [7] and usually accepted for the radius of plasma column created by charged particle at the time just after thermalization of carriers. In the present work we attempt, within the framework of the second concept, in accordance with formula (1), with fixed R_0 value of 1.15 μm [7] to extract the value of b in the form of its dependence on electric field from our measured spectra for ^{34}S and ^{40}Ar ions. This step is well grounded from the viewpoint of Shockley phenomenological approach to the avalanche multiplication in semiconductors which predicts the increase of the parameter of ionization, b, for relatively high fields [8]. The value $\Delta Q/Q_r$ was defined as $(Q_m\text{-}Q_r)/Q_r$, where Q_m and Q_r are the centers of gravity of multiplied and regular peaks, respectively. Our choice of sulphur and argon ions is based on the possibility, for these particles, to produce well resolved multiplied peaks in silicon surface barrier detectors (SSBD). It simplifies the measurement of the value of $\Delta Q/Q_r$ by conventional spectrometry technique, namely: charge preamplifier — shaping amplifier — analog to digital converter. ^{34}S and ^{40}Ar ions were accelerated by the U-400 cyclotron of FLNR, JINR, and, after scattering to the angle of 25°, were detected by the SSBD. As an example, in fig.1a,b the spectra of ^{40}Ar with two peaks and ^{22}Ne without multiplied peak, are shown. In the fig.2a,b,c,d the measured spectra of ^{34}S ions are presented for different biases applied to the detector to show the development of the multiplication process.

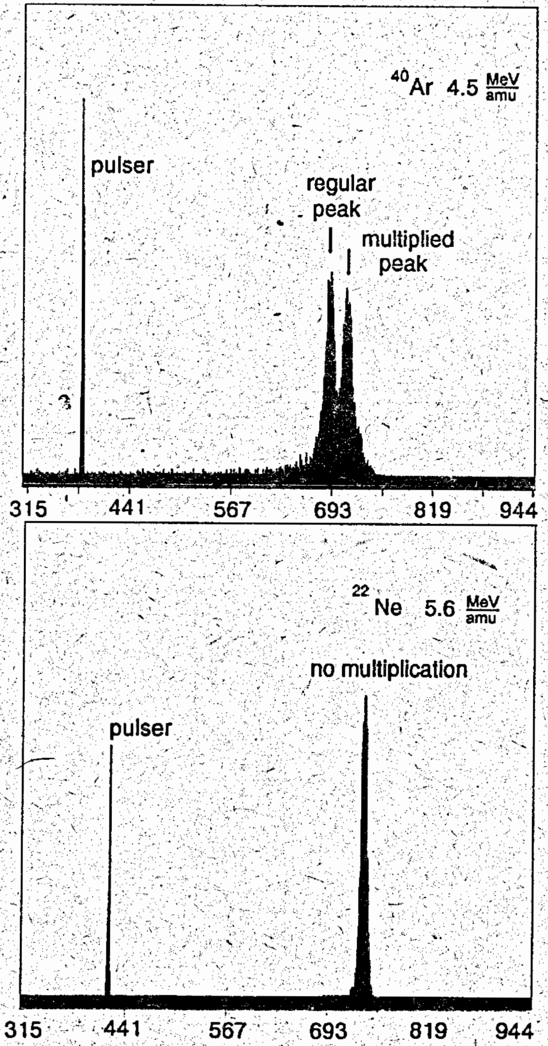
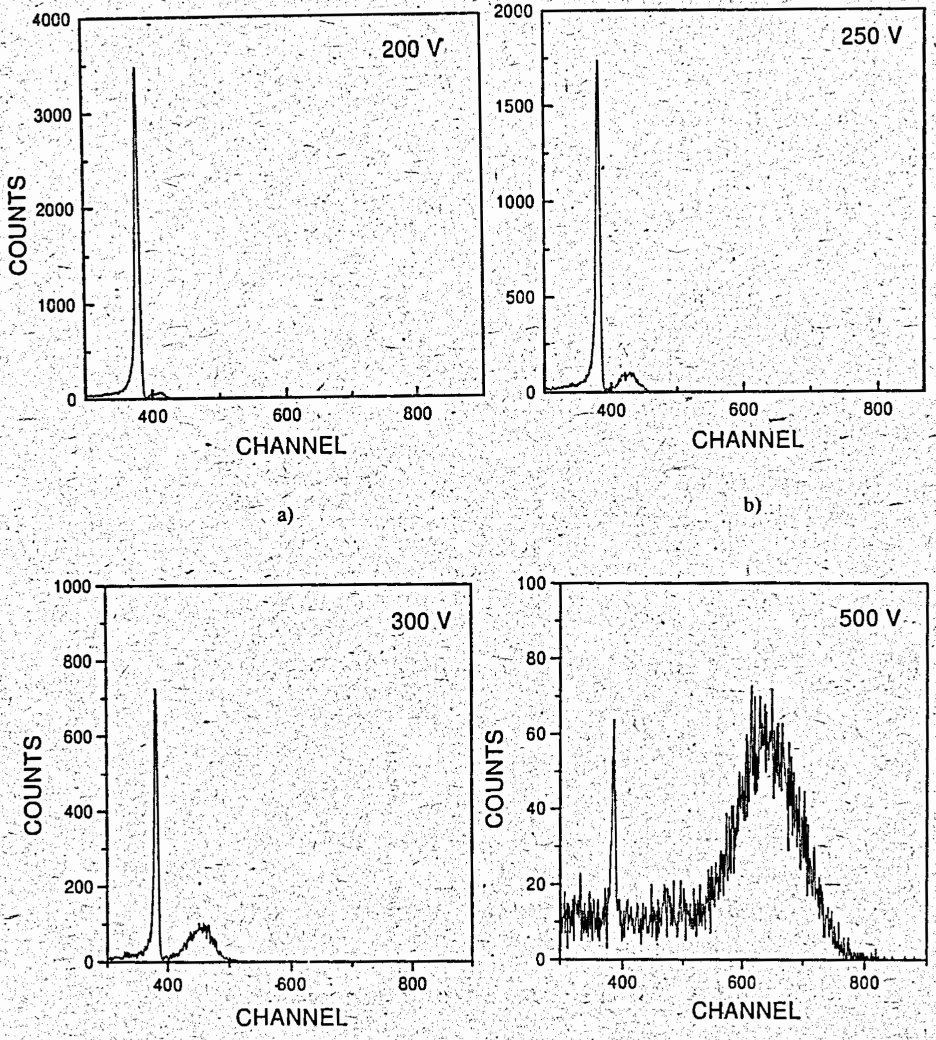


Fig1. The pulse distributions for ^{40}Ar (a) and ^{22}Ne (b).



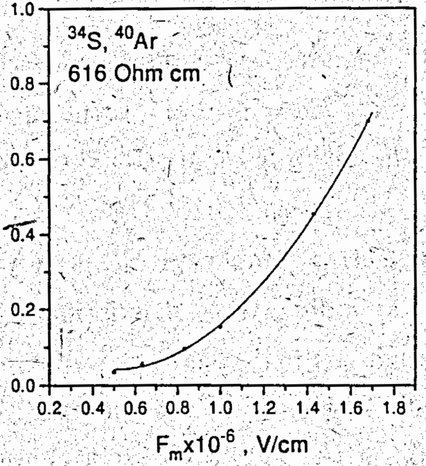
a) b)

c) d)

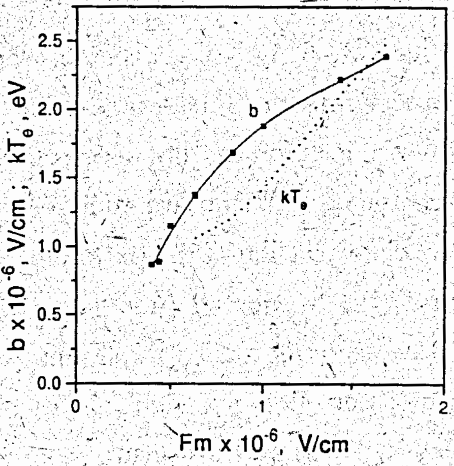
Fig2: The pulse distributions for ^{34}S.
a - 200 V, b- 250 V, c-300 V, d-500 V.

TABLE

ion	energy, MeV	electron-hole concentration $x10^{-17}cm^{-3}$	observation of multiplication
^{10}B	40	0.27	-
^{12}C	90-130	0.38-0.30	-
^{18}O	100-180	0.92-0.69	-
^{22}Ne	100-150	1.36-1.18	-
^{24}Mg	120-160	1.42-1.29	-
^{34}S	200-220	2.31-2.15	+
^{40}Ar	160-320	2.49-2.25	+
^{40}Ca	210	2.73	+
^{58}Ni	290	4.16	+
^{68}Zn	400	5.09	+
^{136}Xe	100-140	4.36-5.08	+



a)



b)

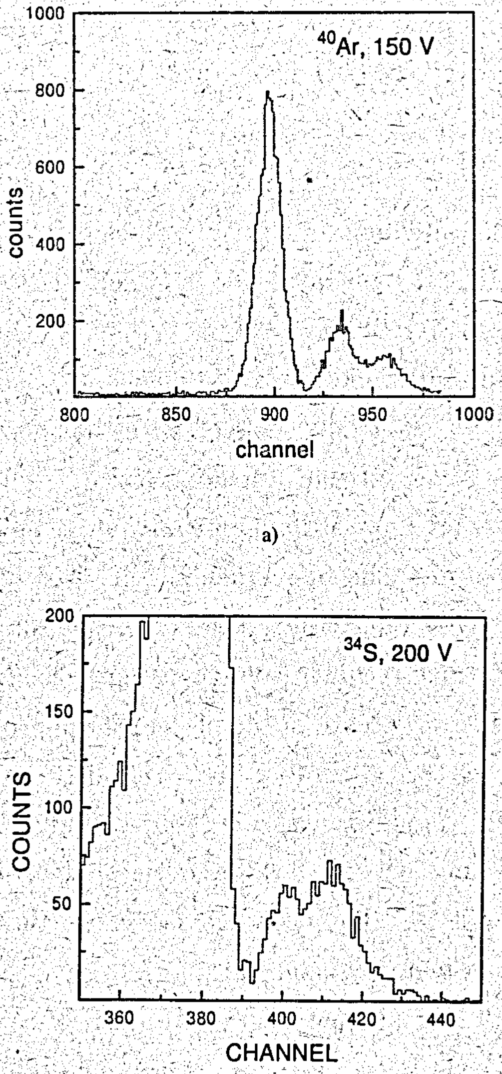
Fig.3a The dependence of parameter dQ/Q against the electric field.
Fig.3b The dependance extracted ionization constant b and the temperature of hot electron versus the electric field.

In fig.3a,b the values of dQ/Q and extracted values of b are shown against the value of electric field F_m taken as $F_m = h/R_0 \times F_0$ and $F_0 = 2V/d(1 - h/d)$ according to [6], where V is the detector bias and d —the depletion layer thickness, h —the particle range in silicon. In fig.3b four points which correspond to 1.1 MeV/amu ^{136}Xe ions [5], 8 MeV/amu ^{40}Ar (data from [4]), and two points for 6.4 MeV/amu ^{40}Ar (this work) were added. The numerical values of the parameter b lie mainly within the range well known from physics of semiconductors [9]. The obtained dependence allows to estimate the temperature of hot electrons, since it is related to the b/F_m value by the equation

$$kT_e = \frac{E_i^2}{2E_R^*}\left(\frac{F_m}{b}\right)^2 \qquad (2),$$

where $E_i = 1.1$ eV, is the threshold carrier energy above which the carrier may produce a hole-electron pair, $E_R^* = 0.12$ eV, is the mean energy loss for the hot electron on the mean-free-path L_R between scattering by "Raman" modes [8].

The variation of the parameter of electron temperature T_e is shown in fig.3b by dotted line. The corresponding vertical axis has the same scale as for b value. Due to high temperature of the electron subsystem it is possible to observe the influence of the complicated conductive band structure of silicon on the development of charge multiplication, which means that, the carriers corresponding to different valleys can take part in this process. As a manifestation of this influence one can anticipate the observation of more than one peak in multiplied mode. We do observe this for both sulphur and



a)

b)

Fig.4 The spectra of ^{40}Ar and ^{34}S ions, demonstrated two modes of the charge multiplication.

argon ions, although, for the last case the presence of two multiplied modes is more evident (fig.4a,b). Concerning this effect and following the philosophy of [10] we can state that lighter electrons are more easily accelerated by the electric field and should attain higher mean energy than the heavier ones. On the other hand, when the applied field is high enough for the electrons in colder valleys to have energies sufficient to emit intervalley phonons, the role of different groups of electrons is smoothened. As a result we should observe only single common multiplied peak. We also should note that the obtained value of T_e=1–2.5 eV agrees well with that given by Shockley as being of the order of one electron-volt. The above results indicate that the second concept has some advantage as compared to the first one in explaining the phenomenon of charge multiplication in silicon detectors. As one of its drawbacks, one should note an absence of those parameters which could take into account some critical electron-hole plasma density needed to start the process. This is illustrated in fig.1b as well as in tab.1 in symbolic form, where "–" denotes that no multiplication was observed for any bias value up to near-breakdown ones, whereas "+" denotes that charge multiplication took place under definite conditions. Note, that the role of plasma density was reported already in [2], but only within the first concept. Within the second concept, the influence of plasma density can be noticeable if one takes into account the possibility, especially in the starting moment, of the two-particle (or two-step) processes for which the threshold of ionization could be less than that for conventional single-particle (single step) ionization, due to the summing of the carrier energies [8,9]. We do not exclude the mechanism of electron heating by electric field when the relation $\tau_{ee} << \tau_p << \tau_e$ is valid (here τ_{ee} is the average time interval between electron-electron collisions and τ_p and τ_e are the momentum and energy relaxation times, respectively). In this case the heating of carriers is more efficient, because of enhanced energy exchange between them. Of course, the above relation is satisfied better for lower τ_{ee} values and, hence, for higher plasma densities. Irrespective to the concept, one should note that nearly up to breakdown we have observed a regular mode. We consider this observations to be related to the time limitation of the process. As to the parameters, which can limit the process, we can evidently consider the plasma errosion time and, probably, the lifetime of high local field, which can be even shorter. Due to these reasons, taking into account that for every electron the probability per time unit to start an avalance is finite, we can state that the total probability of charge multiplication for every given incident particle is also finite and increases with the field value. From this viewpoint the value of $P(F_m) = N_m/(N_m + N_r)$ should be considered as equivalent to that probability. Here N_r and N_m are the sums of the regular and multiplied peaks, respectively. As to our nearest plans, we hope to measure the spectra for different heavy ions as well as to estimate contribution of two-particle ionization in a quantitative form.

References

[1] M.C.Britt and H.E.Wegner Rev. Sci. Instr., vol.34, N 6, (1963) 627.

[2] F.J.Walter IEEE Trans. Nucl. Sci., NS-11, N 3 , (1964) 232.

[3] H.M.Heijne et al. IEEE Trans.Nucl.Sci., NS-25, N 1, (1978) 378.

[4] W.F.Kushniruk, Guin Thi Ha and Yu.S.Tsyganov Pribory I Tehnica Experimenta, N3, (1989) 57. / in Russian /

[5] W.F.Kushniruk and Yu.P.Kharitonov JINR communication N 13-9836, Dubna, 1976.

[6] E.M.Verbitskaya et al. Fysika I Tehnika Poluprovodnikov, vol.21 N 8, (1987) 1388.

[7] W.Seibt, K.Sundstrom and P.Tove Nucl. Instr. & Meth., 113 (1973),317.

[8] W.Shockley Solid State Electronics, vol 2, No. 1., (1961), 35.

[9] I.W.Grekhov and Yu.N.Serejkin "Lavynni Proboj V Poluprovodnikah", Leningrad, "Energia", 1980, p.29. / in Russian/

[10] C.Canalli, G.Ottaviani and A.Alberigi Quaranta J.Phys.Chem. Solids, vol.32 (1971) 1707.

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