Charge Accumulation on Metal Strip-detector Sensors
Under Ion Beam Irradiation: Experiment and Modeling

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Abstract. This paper presents the Monte-Carlo simulation in aluminum film with the thickness of several tens micrometers, which is a part of metal strip-detector sensor. It was believed that ions Cu\(^{++}\) with energy 5–25 keV are generating secondary electrons. Elastic collisions with target atoms, atomic levels ionization and electron capture have been taken into account for the ions, and for the secondary electrons—elastic collisions with target atoms, atomic levels ionization, plasmons and phonons generation. It has been obtained that an accumulated charge dependence on ion beam energy matches with experimental data.

Introduction

Metal strip-detectors are used to detect and control the parameters of the fast particles beam for about ten years [Pugatch et al., 2007, 2011]. They are distinguished by a number of advantages, including extremely high radiation stability, compactness, high positional accuracy, ease of use. Meanwhile, a more detailed study of physical phenomena occurring in metal strip-detector when passing fast charged particles is needed for their properties improvement. In this area there is a wide range of processes for detailed study and modeling, including: (1) fast multicharged ions interaction with metallic films; (2) generation and evolution of the secondary electrons swarm; (3) the substrate and the external electric fields influence on the secondary electron emission from the film and the charge accumulation on it. The Timepix chip has a matrix of \((256 \times 256)\) identical pixel elements, designed in a commercial 0.25 \(\mu\)m six-metal CMOS technology. Each readout pixel includes preamplifier, discriminator and counter and can be independently configured to provide information of arrival time, time-over-threshold or event counting.

In this paper the main attention is paid to modeling secondary electrons generation and evolution inside the metal film and the charge accumulation on it. Since the electron beams are the basis of electronic spectroscopy, Auger-spectroscopy and other techniques.

Experimental setup

The Timepix detector was mounted in a vacuum chamber on a movable platform at the focal plane of a laser double-focusing mass-spectrometer. Scheme of the ion path in a laser mass-spectrometer is shown in Fig. 1 [Pugatch et al., 2011].

Ions are desorbed from the sample-target surface (2) by a pulsed infrared (1064 nm) laser (1) (15 ns, 50 Hz). The ion beam width is defined by the slits (5, 6, 8) and was in the range of (20–2000) \(\mu\)m. When passing through the magnetic sector (9) the ions were focused spatially and separated according to their mass over charge ratio along the focal plane (11) of the magnetic sector (9). The metal micro-pixel detector (10) is a bare readout chip with its input contact pads used as metal sensors. An external metal grid is positively biased with respect to the input pads to improve charge collection.

Figure 1. Schemes of the ion path in a laser mass-spectrometer: 1—laser, 2—target, 3, 4—accelerating electrodes, 5, 6, 8—beam shaping slits, 7—energy analyzer, 9—sector magnet, 10—TimePix chip, 11—focal plane.
The Timepix (Metal) detector is the Timepix readout chip detecting ions directly at the metal octagonal electrode of its pixel input stage. This allows to exclude a 300 μm thick semiconductor sensor from a detection chain with an obvious advantages, like in Timepix hybrid detector, for a performance of a mass-spectrometer.

Model

Described system can generate ions with charge $1^+, 2^+, 3^+$ and $4^+$ and energy (3–40 keV), but ions with charge are $2^+$ generated more intensively so we will consider only them. Fast ion is exposed to different collisions types with atoms and electrons while moving through the strip detector film. Electrons that were created by ionization of atoms, in their turn, trigger a number of collisions, which can also lead to the emergence of next electrons generation, etc. In the cascades evolution the crucial role is played by the collisions probability, so we will consider the majority of known processes.

For the experiment simulation Monte-Carlo model was used, in which the particles mean free path is calculated by the formula

$$\lambda = 1/\sigma_{\text{tot}} n,$$

where $n$—atomic concentration in the target, and $\sigma_{\text{tot}}$—cross-sections sum of all processes. Once the particle has passed the distance, described by equation $e^{-1/\lambda}/\lambda$, it dissipates through one of the following processes. Process of scattering a particle in a given state was played from condition that the probability of the $i$-th process is equal $\sigma_i/\sigma_{\text{tot}}$.

The ions elastic collisions with the film detector atoms were considered in the classical model of paired collisions. This model is valid when ion trajectory becomes asymptotic on distance $a/2$ ($a$—average interatomic distance). In this work we considered that this condition is fulfilled if the minimal distance between ion and atom in a collision is $a/2$ Makarets and Storchaka, 2001. It can be created radiation defect if the energy loss more then energy needed for creating ones (66 eV for aluminium). In this case generates free aluminium atom, which modeling like copper ion with own cross sections.

The n-th atom shell ionization with binding and kinetic energies of $U_n$ and $K_n$, respectively, and occupancy $n_n$ was considered in the Gryzinski model [Gryzinski, 1965; Kaganovich et al., 2006], which is valid in the case of Coulomb interaction between ion and atom electrons. When calculating the scattering angles of ion, ionized atom and electron model described in Fedoreenko, 1959 was used. The secondary electron has energy not more than hundreds of eV at the mentioned above incident ions energies range. In [Gryzinski, 1965] ionized atom motion is not included, and from conservation laws implies that the scattering angle of ion is $\theta \approx 0$, and of secondary electron $\theta_s \approx \pi/2$, and its energy is $E_s = T − U$, where $T$—transferred energy from ion to atom.

Electron capture by ion is used according to [Gryzinski, 1965]. Ion kinetic energy increases by $U_n − U_f > 0$ after electron capture ($U_{n,1}$—electron binding energy in the film atom before and in ion after capture). If $U_n < U_f$, then total cross section becomes singular at $E \approx (U_f − U_n)/m_e$. In this case total cross section is calculated according detailed balance [Garcia et al., 1968] and the kinetic energy decreases by $U_f − U_n > 0$. Electron capture does not change an ion direction.

Ion stripping also does not change its velocity direction. The total cross section of this process is inversely proportional to its squared charge $1/Z_i^2$ [Beits, 1966; Briggs and Taulbjerg, 1978]. It means that for high ionization levels big energy is needed. So we’ll consider only total cross-section

$$\sigma_s = \frac{\sigma_0}{E} \int_{q_{\text{min}}}^{\infty} dT \int_{q_{\text{min}}}^{\infty} dq |F_p(q)|^2 |F_t(q)|^2$$

(2)

where $q$—impulse transfer, $T$—energy loss in collision, $q_{\text{min}} = T/\nu$ (where $\nu$—ion velocity, $F_p, F_t$—form factors of particle and target atom which accordingly equal to: $F_p = (T|e^{i\phi}|0)$, $F_t/Z_t = 1 − (1 − (q/2\xi)^2)^{-1}$, $\xi$—electron shell screening constant (for copper 4s-state $\xi = 5.84$).

Elastic electrons scattering on atoms is calculated according to the quantum model of pair collisions [Mott and Messi, 1969]. Aluminum atom mass is much greater then electron mass, therefore electron energy in C-system after collision nearly equals to electron energy in C-system before collision. This process just changes electron direction.

To calculate the differential and total cross-sections of atomic levels ionization for collisions with electrons the Kim-Rudd semi-empirical model was used Kim and Rudd, 1994; Hwanga et al. 1996. After ionization we will obtain three following particles: 1) scattered electron with energy $E − T$, 2) Ionized atom with energy $E_{n}$. 3) Secondary electron with energy $E_s = T − U_i − E_{n}$. Total cross section of low atomic levels is several orders smaller than total cross section of highest levels.
To calculate the total cross-section of plasmons generation and secondary electron ionization from the conduction band the Penn model [Penn, 1987] was used with experimentally measured loss function $3 \left( \varepsilon^{-1}(W) \right)$ for Aluminum (data from DESY), that was analytically extended to the $Q$ axis, $W$—plasmon energy, $Q$—secondary electron energy, which ejected from conduction band.

**Results and discussion**

The simulation in which the aluminum film with thickness of several tens of micrometers was irradiated by Cu$^{++}$ ion beam was carried out. In program during the copper ion movement in the film it had been forming secondary electrons, which in their turn formed a tertiary ones, etc., therefore on the output from the film along with positively charged copper ions secondary electrons were observed. Also, electrons were ejected in the opposite direction. When an electron or ion approaches close to the target surface, they can either go outside or reflect from it. Particle can overcome the barrier only if its velocity component normal to the surface in energetic units is more than work function. Otherwise, the particle will reflect from the surface.

In Fig. 2(left) shows the dependence of the accumulated charge on detector. Total charge calculating as:

$$Q = Q_{\text{ion}} - Q_{sp} - Q_{bel} - Q_{fel}$$  \hspace{1cm} (3)

where $Q_{\text{ion}}$—total charge of ions, which are stuck in the film, $Q_{bel}$—charge created by electrons which emitted in the opposite direction, $Q_{fel}$—charge created by secondary electrons which emitted in the primary ion beam direction, $Q_{sp}$—charge created by sputtered atoms. The contribution made by each of them is illustrated in Fig. 2(left). We are not considering charge formed by electrons emitted in primary beam direction, because their number one order less then back scattered electrons. Also sputtered atoms are ejected not charged, because they have energy not enough for stripping. We are obtained that sputtering coefficient is 3.1 for incident ion beam with 5 eV energy. This one corresponds to the values obtained by Matsunami et al. 1983 and [Sigmundt, 1969]. From the experimental data we know only absolute value of the accumulated charge. We had normalized the experimental data by one, because irradiation dose is unknown. As you can see the contribution of SEE in accumulated charge is about 10% of total value at high ion energies.

Since in the experiment, the sensor film thickness is known only approximately, we performed calculations for the number of thicknesses and picked up the one for which calculation results and experimental data were most similar. It was established that when film thickness is greater than 1 $\mu$m number of secondary electrons ceases to depend on the thickness. Fig. 2(right) presents a comparison of calculations for different film thicknesses. It shows that accumulated charge per ion decreases for small thicknesses of film and with the reduction of ions energy, because the ions do not have time to ionize target. Ions mean free path is proportional to its energy. On small film thickness they have few collisions. And ion energy loss is proportional to collisions number, therefore they can’t stuck in the "thin" film. In opposite, for big film thickness, low energy ion can’t give enough energy to the secondary electron for ejecting from the film. Also at low energies, ion loses its energy in elastic collisions with big scattering angle whereupon it is ejecting back and charge is not accumulated on the film. Thus accumulated charge is limited by zero at small thickness and high ion energy, and is the same for all thicknesses at low ion energy.

Simulation showed that the charge $Q_{bel}$, that was formed by secondary electrons is proportional to the number of ionization collisions inside the film. This number increases with film thickness enlargement and is decreasing with ions mean free path lowering. Secondary electrons are ejected only from a thin layer closed to the surface, so their number reaching saturation with increasing film thickness at constant incident ions energy, as shown in Fig. 3(left).

Although the ions energy considered in the work are not enough to ionize the target atoms, but the secondary electrons are generated in the ion beam ionization process. It can be obtained from (2) that the cross-section of projectile ion ionization is proportional to $\sigma_s \sim 1/E^2$, therefore ions mean free path (1) between secondary electrons formations is invert proportional to the square of the particle energy. This is confirmed by Fig. 3(right), where is illustrated that relation $QE^2 \sim d$ is linear for small sensor thickness. With increasing target thickness linearity is violated—firstly decreases and then after 1 $\mu$m reaches stationary level Fig. 3(left).

These qualitative dependences allow to evaluate one of the three variables (created charge, primary beam energy, target thickness) when other two values are defined.
Figure 2. Left. The dependence of the accumulated charge on the Al film with 50 µm thickness on the incident ions Cu$$^{++}$$ energy. Right. The dependence of the accumulated charge on the Al film on the incident ions Cu$$^{++}$$ energy and film thickness.

Figure 3. $QE^2 \sim d$ relation, where $Q$—charge created by secondary electrons, which are ejected from a film surface. Left. For big film thickness ($\geq 1\mu m$), Right. For small fill thickness ($\leq 50nm$)

Conclusion

Charge accumulation in metal films was investigated by computer simulation of low energetic ions and electrons classical movement. The cross sections of elastic and inelastic collisions obtained in the framework of quantum mechanics were used. Calculated dependence of the charge coincides fairly well with experimental data for the ion energies from 5 to 25 keV, although created secondary electrons have the de Broglie wavelength much more than the interatomic distance into the film. Within of the model it is possible to calculate secondary electrons spectra, angular distribution of particles emitted from the film, spatial distribution of “stopped” particles and so on.

Proposed model of particles movement will be refined in next articles for more accurately account of interference effects, when de Broglie wavelength is larger than the interatomic distance.

References