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A new physical model of the performance of avalanche photodiodes with single photoelectron detection

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A new physical model of avalanche process with single photon detection capabilities is presented in various Geiger mode photodiodes. The model describes development of avalanche process in time, taking into account the space charge resistance as well as the change of electric field in the avalanche region caused by internal discharge and external recharge currents. Results of simulations are compared with experimental data received with Geiger mode photodiodes from different suppliers. It was found that at fixed overvoltage the signal gain is reduced significantly depending on the space charge resistance. The relative value of the reduction in signal gain depends on the pixel capacitance. The possibilities of improving the parameters of avalanche photodiodes are discussed widely in this work.

I. MODEL OF AVALANCHE PROCESS IN MICRO PIXEL AVALANCHE PHOTODIODE

New equivalent circuit of a single pixel operating in Geiger mode is described in Fig.1. We propose a simple model of performance of the MAPD pixel containing a *p+-i-n+* structure with an individual quenching microresistor *R*p. Resistance (Rs) of space charge region of pixel, terminal capacitance (Cp) of pixel and parasitic capacitance is taken into account in this model. One photo-electron is created near the anode (N_{01}=1) at time t = 0. This electron passes through the i-layer during the time $\tau=W/v$, where v is drift velocity, and creates electron-hole pairs near the cathode. Number of electrons N_1 collected at the cathode, number of holes P_{02} moving toward the anode, and electric field E_1 during this stage can be expressed as $N_1=\exp(\alpha_1 W)$, $P_{02}=[\exp(\alpha_1 W)-1]$, $E_1=(U_1/W)$, where $\alpha_1=\alpha(E=E_1)$ and $U_1=U_d$. The holes with quantity $P02$ move towards the anode and create near its new electron-hole pairs after another period of time τ. All these holes are collected at the anode and a new number of electrons N_{02} start the second stage of the avalanche: $N_{02}=[\exp(\alpha_1 W)-1]\times[\exp(\beta_1 W)-1]$ where $\beta_1=\beta(E=E_1)$. And so, new electrons appear near the anode after every time period 2τ, starting a new stage of the avalanche. As a result, the number of electrons collected at the cathode after the second stage of avalanche process is $N_2=N_{02}\times\exp(\alpha_2 W)=[\exp(\alpha_1 W)-1]\times[\exp(\beta_1 W)-1]\times\exp(\alpha_2 W)$. Hence, the number of electrons collected at the cathode after the *i*-th stage is $N_i=\Pi\{\exp(\alpha_{i-1}W)-1]\times[\exp(\beta_{i-1}W)-1]\}\times\exp(\alpha_i W)$ $i\geq 2$; $M=N_1+\sum_{i=2}N_i$

During avalanche process capacitance (C_p) is discharged and due to it voltage (U_{si}) drop on the spark gap decreased. Internal discharge current due to the avalanche process is $I=qN_i/(2\tau)$ We obtained U_{si} voltage change as following form

$$U_{si}=U_{s(i-1)}+\frac{U_d-U_{s(i-1)}}{(C_p+C_q)\times R_q}\times 2\tau-\frac{q\times N_{(i-1)}\times R_s}{(C_p+C_q)\times R_q}-\frac{qN_{(i-1)}}{(C_p+C_q)}-R_s\times\frac{q(N_i-N_{i-1})}{2\tau}$$

When avalanche process is quenched the diode capacitance (C_p) is charged by J the external current through R_q resistance to the applied voltage (U_d). The external current is change as following form

$$J_i=\frac{C_p(U_d-U_{s(i-1)})}{(C_p+C_q)\times R_q}-\frac{C_pR_sqN_{(i-1)}}{R_q(C_p+C_q)\times 2\tau}+\frac{q\times N_{i-1}}{2\tau}\left(\frac{C_q}{(C_p+C_q)}\right)$$

Gain (*M*) of the MAPD pixel for a single initial photo electron can be calculated as : $M=C_p(U_d-U_{si.min})/q$

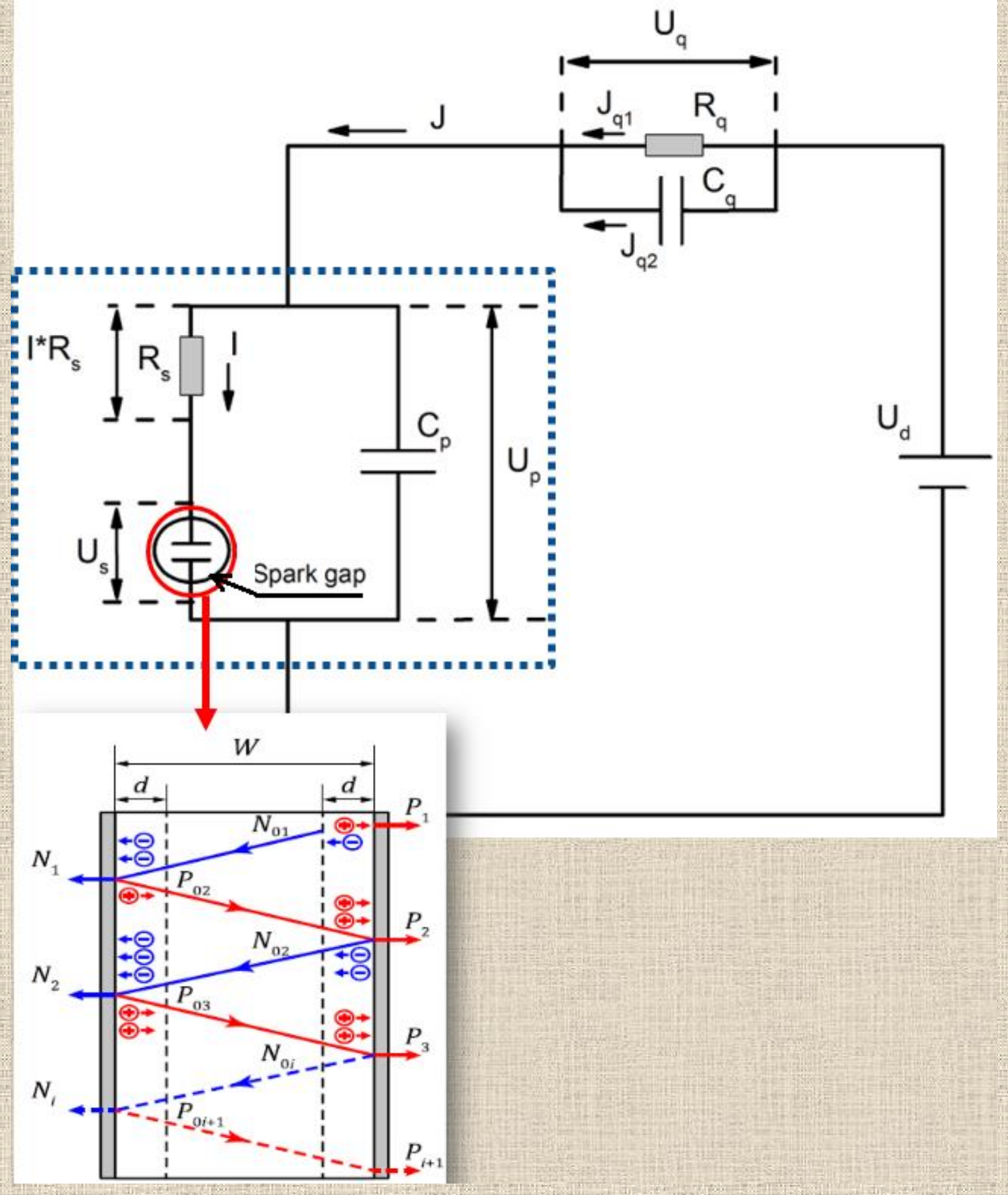

Fig .1 Equivalent circuit of a single pixel operating in Geiger mode

II. CALCULATION AND COMPARISON WITH EXPERIMENTAL DATA

Single photoelectron avalanche processes have been investigated in single-pixel and multi-pixel MAPDs from two producers. In order to understand the internal process of avalanche development, it is important to know number of electrons N_i created during each cycle of the avalanche process. Calculations of a single-pixel avalanche photodiodes fabricated by Zecotek Company and Laser Components Company show that the value of N_i rises sharply within a few cycles and reaches its maximum value N_{max} at U_{br}. Thereafter, it falls at the same rate. These charge carriers leads to further drop of pixel potential well below the breakdown voltage. As a result, the avalanche process is rapidly quenched. The total potential drop reaches $4V=2\times\Delta U_P$, where $\Delta U_p=U_d-U_{br}$ is overvoltage. Physically, the maximum number of charge carriers in the avalanche cycle must be reached at $U_P=U_{br}$. Many researchers studying MAPD (or MPPC) devices believe that this linear dependence can be used to determine the pixel capacitance C_P taken to be equal to $C_{eff}=\partial Q_e/\partial U_d$. However, our model demonstrated that this is not the case and $C_{eff}=2\,C_p$ when we took $Rs\sim 0\Omega$ in our previous work [www.arcjournals.org/pdfs/ijarps/v3-i2/3]. As a result, $Q_e=C_{eff}\times\Delta U_P=C_p\times 2\Delta U_P$. However, this is not true for devices having large area.

We have studied a micropixel avalanche photodiode and a single-pixel avalanche diode fabricated by Zecotek Company. An external series resistor of R_p=100 kΩ has been used for quenching of avalanche process. The active (photosensitive) and contact areas of the single-pixel photodiode are 34μm ×34μm and 100μm ×100μm, respectively. Total terminal capacitance of this device is C_p=0.9 pF. Figure 2 (a.) shows dependence of the single photoelectron charge upon the applied voltage. One can see that the effective pixel capacitance calculated using the expression $C_{eff}=\partial Q/\partial U_d$ is C_{eff}=1.7 pF, which is approximately twice the value of the measured terminal capacitance C_p.

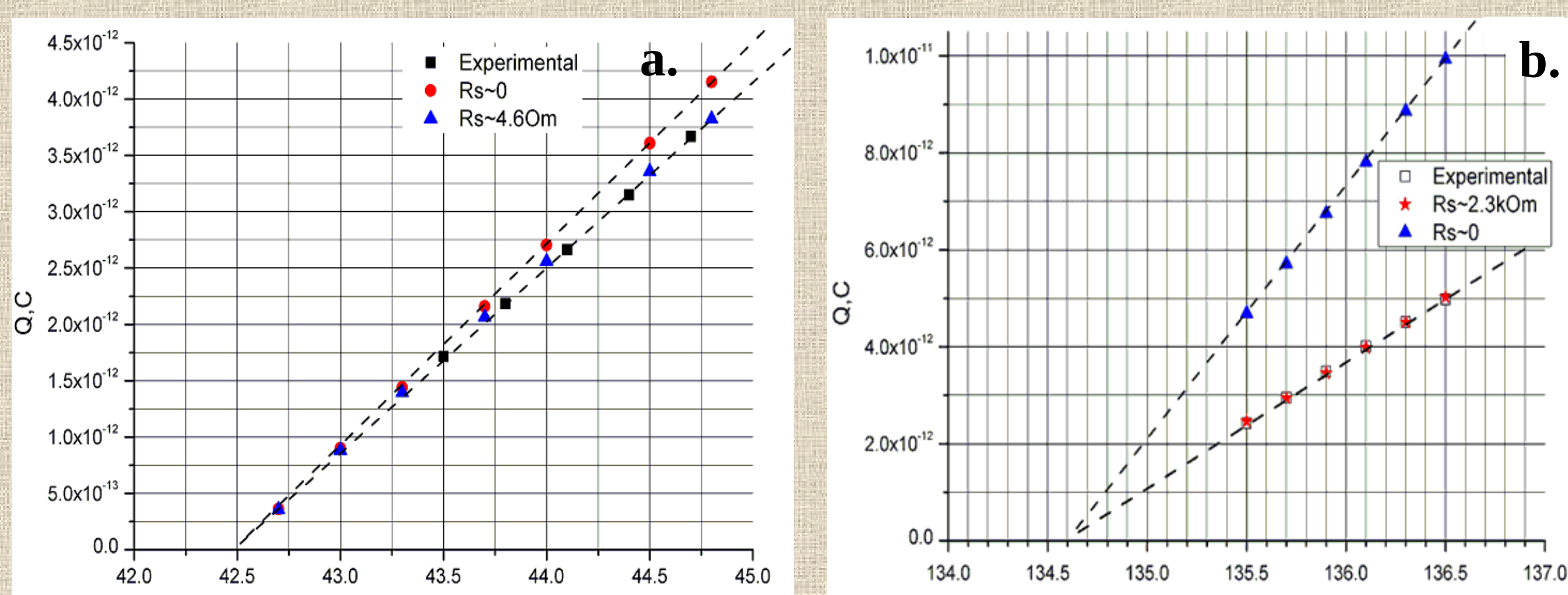

Fig.2 Charge of single photoelectron pulses as a function of the bias voltage measured in the Zecotek device (a.)and the Laser Components (b.).

The second one-pixel avalanche photodiode with serial number R4523 have been received from Laser Components Company (www.lasercomponents.com), which consisted of two elements: a small area photodiode and an external quenching resistor R_P=100 kΩ. The active diameter and the width of depletion region of the photodiode is 500μm and 25μm. Total terminal capacitance of the device is C_p=2.6 pF. Figure 2 (b.) shows dependence of the single photoelectron charge upon the applied voltage. One can see that the effective pixel capacitance calculated using the expression $C_{eff}=\partial Q/\partial U_d$ is C_{eff}=2.7 pF, which is approximately equal to the measured capacitance C_P of the pixel. Our result demonstrates that this is not the case and $C_{eff}\approx 2C_p$ in small area pixels. As a result, $Q=C_{eff}\times\Delta U_p=C_P\times 2\Delta U_p$. This means that after suppression of avalanche process the pixel potential drops below the breakdown voltage by the overvoltage value ΔU_p. This difference is explained with high resistance of depletion layer of the device R4523. Resistance of depletion layer is calculated following form [Physics of Semiconductor Devices, S. M. Sze 1981]

$$R_s=\frac{W^2}{2\varepsilon\times\varepsilon_0\times S_p\times v_s}=\frac{W^2}{2\varepsilon\times\varepsilon_0\times\frac{\pi\times L^2}{4}\times v_s}=\frac{2}{\varepsilon\times\varepsilon_0\times\pi\times v_s}\times(\frac{W}{L})^2=61kOhm\times(\frac{W}{L})^2$$

where W-width of depletion region, L- diameter of single electron avalanche channel, ε-dielectric permittivity and v-drift velocity of charge. Internal current in the device R4523 is very high (Fig .3-a, ~0.35mA) and that is why some voltage drops on R_s ($I*R_s$= 0.35mA*2.3k Ω =0.8V). Overvoltage and gain of pixel decreases with R_s (Fig. 3-b). When Rs is 2.3k Ω experimental and simulation gives same results (Fig. 2-b) however when R_s reaches about 0 Ω total charge increases 2 times. In this case C_{eff} is $2C_P$ and simulation results for both diodes have been experimentally confirmed.

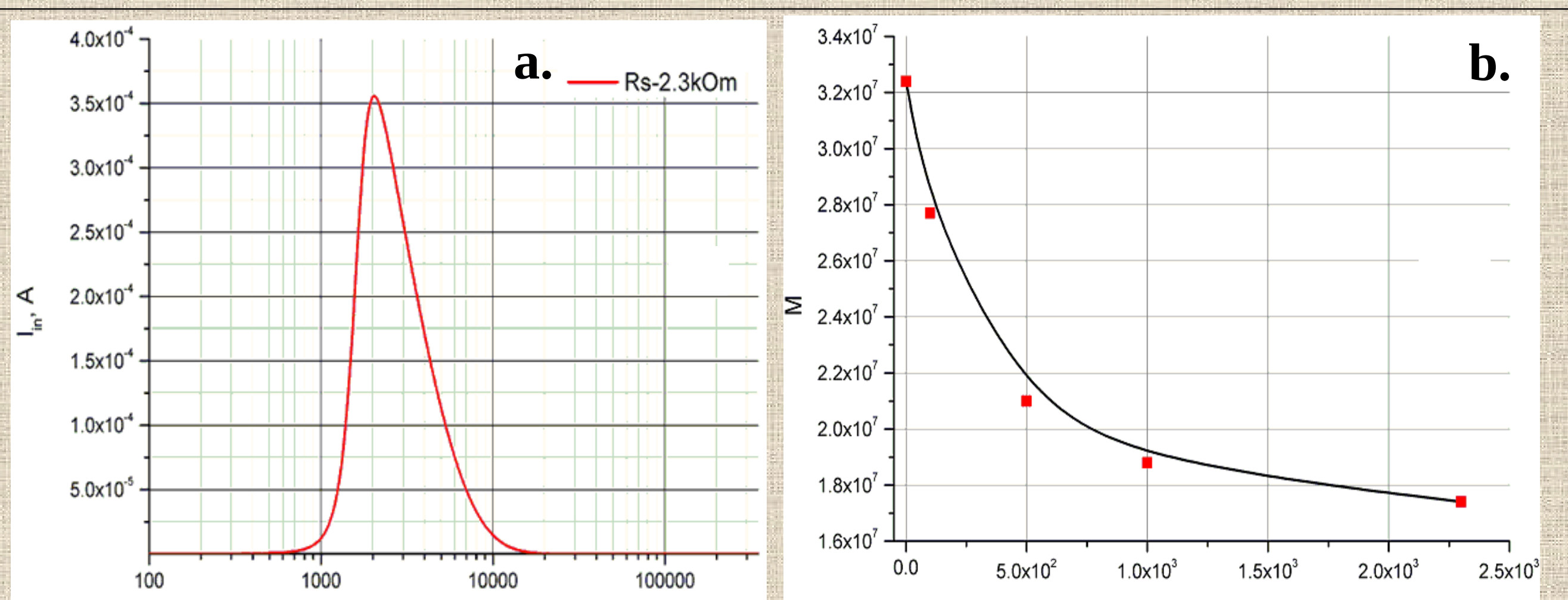

Fig.3 Time dependence of internal current (a. V-135.6V) and the gain dependence of R_s (b.) in the device from Laser Components.Comp

The new model also allowed to study the influence of the pixel capacitance, resistance of depletion region, parasitic capacitance and applied voltage on the time characteristics of SPAD. Simulation was performed for MAPD that has capacitance of C_p=20fF, V_{br}~60V and the quenching resistor of 500kΩ. The results showed that the rising time of single photoelectron (U_{ap}=63V) decreases with increasing parasitic capacitance and when the parasitic capacitance is greater than 10^{-16}F then the rising time of single photoelectron saturated and reached 100psec (Fig.4-a). The rise time of single photoelectron decreases as increasing the resistance of the depletion region at same gain and this changing is due to different value of the overvoltage (Fig 4-b). In Fig4.(c-d) is presented the rise time of single photoelectron in the dependence on the voltage and the capacitance of pixel (at same gain). The rise time of single photoelectron decreased with increased voltage, but in the case of the same gain it increased as increasing capacitance. Obtained results of the new physical model of avalanche process for MAPD showed for improving the gain of MAPD at same voltage the resistance of depletion region should be less than 100Ω. The timing performance of MAPD could be improved as increasing the parasitic capacitance and its value should be greater than 1% of value of pixel capacitance.

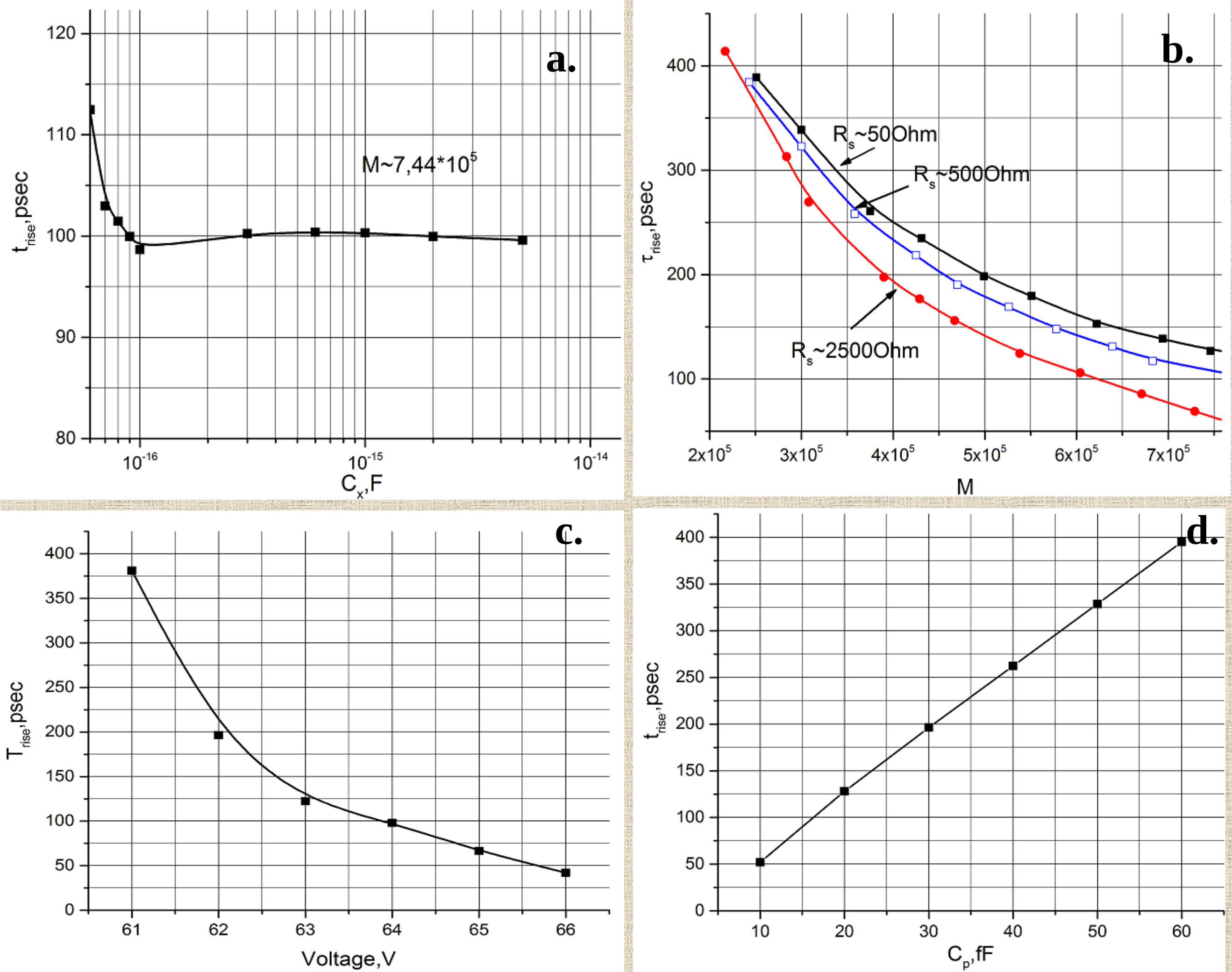

Fig.4 The rising time of single photo electron as a function of the parasitic capacitance (a.) , the gain (b.), the applied voltage (c.) and pixel capacitance (d.)

CONCLUSIONS

The obtained results show that:

- $Q=m\times C_p\times\Delta U_p$ and $C_{ef}=m\times C_p$, where m has values from 1 to 2 and depending on the value of R_s. The more R_s, the smaller m.
- For a fixed value of R_s, the value of m is determined by the capacitance of the pixel C_p. The larger C_p, the smaller m.
- For a fixed overvoltage (ΔU_p), the gain M decreases with increasing Rs.

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