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NEGATIVE CAPACITY OF SILICON AVALANCHE PHOTODIODES WITH DEEPLY BURIED MICRO-PIXELS

E.A. Jafarova [1] **Z.Y. Sadygov** [2] **A.A. Dovlatov** [1] **Z.A. Iskenderzade** [3] **L.A. Aliyeva** [1]
E.S. Taptygov [1] **K.A. Askerova** [1]

1. Institute of Physics, Azerbaijan National Academy of Sciences, Baku, Azerbaijan
celmira1@rambler.ru, alihuseyndovl@rambler.ru, lala1960@rambler.ru, elsalmanel@rambler.ru
2. Joint Institute for Nuclear Research, Dubna, Russia
3. Azerbaijan Technical University, Baku, Azerbaijan, zarifai@hotmail.com

Abstract- This paper presents the investigation results of capacitance of silicon avalanche photodiode with deeply buried micro-pixels of 3×3 μ at alternating signal frequencies f = 50÷300 kHz. It is shown that by applying negative potential to the substrate of structure (involving three series-connected n^+-p-n_{px}^+-p junctions) the first n^+-p junction biased in the forward direction plays the main role. Measured capacitance magnitude increases exponentially with the forward bias U_{for} and at certain value $U_{for} = U_{inv}$ changes the sign becoming the negative capacitance (inductance). The magnitude of active component of complete conduction G grows with the applied voltage and reaches maximum value ~70 mS at U_{for} = 1.0 V and f = 300 kHz. There has been calculated difference in phase φ appearing between current and voltage and it is shown that at U_{for} = 0 V the $\varphi = 80^o$ and passes through the zero at U_{for} = 0.55 V. The magnitude of negative capacitance recalculated to the inductance value with the growth of forward bias being decreased sharply tends to the saturation. Maximum value of L is 50 μH at U_{for} = 0.65 V and f = 100 kHz.

Keywords: Micro-Pixel Avalanche Photodiode, p-n Junction Capacitance, p-n Junction Inductance, Inversion Voltage.

I. INTRODUCTION

For recent years newly developed micro-pixel avalanche photodiodes (MAPD) have gained wide utilization as effective alternative to vacuum photomultipliers. Being compact they have low supply voltage (lower 100 V), high quantum yield (~90%) and low cost. These photodiodes are used at creating devices for scientific research medical and nuclear- physical equipment [1, 2].

MAPD construction involves pixel matrix of individual n^+-regions of 2-5 μ in diameter deeply buried into epitaxial layer of Si p-type conductivity grown on the surface of n-type Si substrate [1, 2, 4-7]. It allows the device of pixel high density for providing wide region of photoresponse linearity to be created [3].

For mentioned structures in the course of avalanche process the part of multiplied charge accumulates in potential well of pixel and runs down the substrate after passing main charge of avalanche. The process of charge accumulation in potential hole is the main process in the mechanism of negative feedback formation of this structure.

Capacitance properties of micro-pixel avalanche photodiodes with deeply buried pixels have been investigated in [4, 5, 7]. It is shown that by applying inverse bias to the structure of three series connected p-n junctions n^+-p-n_{px}^+-p (positive potential is applied to n-Si substrate) the measured magnitude of total capacitance is defined as 1/2 C_1, where C_1 is the capacitance of the first n^+-p junction. It is necessary to note that the capacitance magnitude of the structures under the investigation and its change under the effect of external factors strongly influences on the recovery time parameter of these structures.

Earlier it was shown that in silicon diffusion p-n junctions at high injection levels and fulfilling the condition $\omega\tau \geq 1$, where ω is the angular frequencies (50÷300 kHz) of alternating signal and τ is the lifetime of minority carriers, the change of reactance sign from the capacitance to the inductive one has been observed [8]. It is established that appears of inductive component of conductance is related to the change of basic region conductance.

For ascertainment of inductive-typed impedance mechanism initiation and also mechanism of path of current flow in Si-based micro-pixel avalanche photodiodes, the capacitance has been investigated in forward voltage (negative potential is applied to n-Si substrate with ρ = 7 Ω·cm), and the current flowing through the structure has been measured at one time.

II. MEASUREMENT TECHNIQUE

As a capacitor-meter there has been used the complete conductance bridge allowing the measurement by applying low alternating signal at frequencies (50÷300 kHz).

Bridge supply is made out by G3-7A generator. As a zero indicator there has been used oscilloscope C1-55. As a preliminary the signal was amplified by selective micro-voltmeter B6-1. Stabilized supply power B3-3 provided DC feeds voltage across the sample and adjusted by potentiometer R. Setup contains the capacitor C_1 = 10 μF to provide of keeping measuring part out of the power unit interferences. Capacitance measurement accuracy is ±5 pF. There has been also made thorough protection of samples against the light.

III. PRODUCTION TECHNOLOGY

Diodes under the investigation are made on n-Si with ρ~7-10 Ω·cm as shown in Figure 1(a). To improve field homogeneity on n-Si (1) surface n^+ type thin layer (2) has been formed by ion doping. The choice of as ions instead of conventional P (phosphors) is related to its low diffusion rate at epitaxial layer deposition. Later the growth of the first epitaxial layer (3) of 4 μ in thickness and ρ = 7 Ω·cm has been performed. By photolithography there has been formed the matrix of n^+-region (4) through as ion doping. Then the second epitaxial layer of p-type (5) 4 μ in thickness and ρ = 7 Ω·cm is grown. High-conducting layer of p^+-type (6) has been created by Br ion doping on where aluminum contacts are deposited.

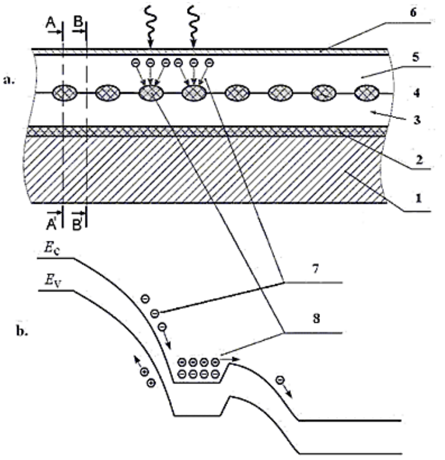

Figure 1. (a) cross section MAPD-3N with deeply buried pixels; (b) energy diagram through section A-A'; 7- is the region of avalanche formation; 8- is the potential well of forward-biased p-n_{px}^+ junction

Simulation impurity distribution in given structures and calculation results of impurity distribution in depth produced by above-mentioned technology of micro-pixel avalanche photodiodes are given in [6]. Thus by performing processing operations there have been created three p-n junctions (section A-A' Figure 1(a): n^+-p, p-n_{px}^+, n_{px}^+-p but in section B-B' not passing through regions n_{px}^+ there has been one p-n junction on the substrate boundary with first epitaxial layer (n^+-p). In Figure 1(b) the diagram of energy levels for A-A' section is given.

IV. RESULTS AND DISCUSSION

As it mentioned in sections going through n^+ regions the structure under the investigation has three series-connected p-n junctions n^+-p, p-n_{px}^+, n_{px}^+-p. In [4] it is shown that the observed dependence of MAPD-3N photodiode capacitance of the frequency at small voltage U_{rev} = 0÷3 V is related to the peculiarity of investigated structure. The presence of matrix of n^+ regions between two epitaxial layers of p-type conductivity leads to the advent of effective resistance between layers. Influence of this resistance on magnitude of measured capacitance depends on the alternating signal frequency.

By negative potential on n-Si substrate the first n^+-p junction biases in forward direction, but the middle p-n^+ junction biases in reverse direction, therefore the first n^+-p junction plays main role in physical processes going in structures under the study.

In Figure 2 there has been presented the dependence $C(U_f)$ at three values of alternating signal frequency: 50, 100 and 300 kHz. At small voltage U_f there has been observed the weak dependence of structure capacitance on the voltage and frequency, i.e. capacitance properties are due to the change of stationary acceptor concentration within the space charge of the first n^+-p junction.

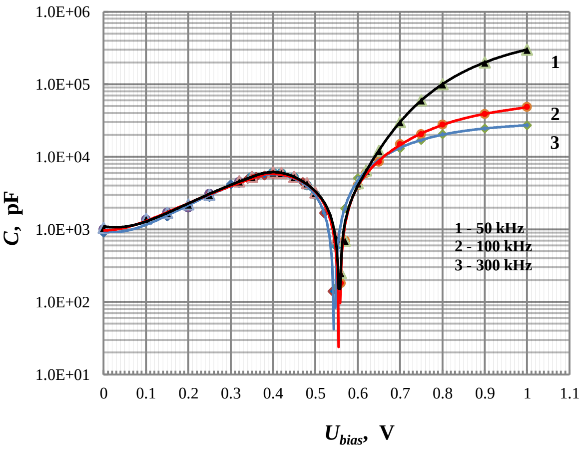

Figure 2. Dependence of micro-pixel avalanche photodiode (MAPD) capacitance on the voltage (negative potential is applied to n-Si) at three frequencies of alternating signal (50 Hz, 100 Hz and 300 KHz)

Beginning with U_f = 0.3 V the capacitance rises exponentially with the applied voltage:

$$C_f = \text{const}\cdot\exp\frac{qU}{\beta_c kT} \qquad (1)$$

where, q is the electron charge, k is the Boltzmann constant, coefficient β_c takes on value β_c ≈ 3-3.5.

In $C(U_f)$ curve at the certain value $U_{\max} < U_{inv}$ there has been observed maximum after which the measured capacitance decreasing down sharply to zero and goes into the negative capacitance (inductance). Voltage of inversion U_{inv} does not depend on the alternating signal frequency and within the experimental error changes over the range (550±5) mV by changing the frequency from 50 up to 300 kHz. Here for the convenience the negative capacitance C^{-} is represented in the first quadrant.

As it is noted above even though MAPD structures under the investigation are made by epitaxial technique [5] the low of capacitance change with applied voltage is the same as for abrupt p-n junctions where unlike linear p-n junctions there is no dependence of inversion voltage on the frequency.

At small voltage applied on the structure, when U_f has order of diffusion potential difference as within the first p^+-n junction as in near contact region of Si substrate the concentration of mobile carriers is low and reactance has a capacitance behavior. With the increasing of U_f the concentration of mobile carriers within the space charge of the first p-n junction rises as much as that it can lead to the change of conductance in basic region. Base resistance modulation can be observed even at small currents yet insufficient for resistance change of all basic region but causing the slow increase of the conductance of its certain part. Changes of basic region conductance tends to exhibit its inertia and the reactance has an inductance behavior.

In paper [8] it is shown that impulse characteristics of voltage on the diode at big injection levels shows the voltage peak as it takes place when the current impulse passing through the inductance. Whereas at low injection levels observed distortion inherent to capacity. Active component of complete conductance G measured immediately on the bridge increases sharply with the applied voltage and reaches its maximum value ~70 mS at U = 1 V and f = 300 KHz.

Knowledge of capacitance magnitude C and conductance G also allows the phase shift between the current and voltage $\tan\varphi = \dfrac{\omega C}{G}$ to be calculated, where $\omega = 2\pi f$ is the angular frequency of alternating signal as shown in Figure 3. As it is seen from the graph at $U_f < U_{inv}$ the angle φ is positive, i.e. reactance has a capacitance behavior but at $U_f > U_{inv}$, $\varphi < 0$ and reactance behaves as an inductance. In inversion point U_{inv} = 0.55 V, $\varphi = 0$ and in this case MAPD structure resistance has a purely active behavior.

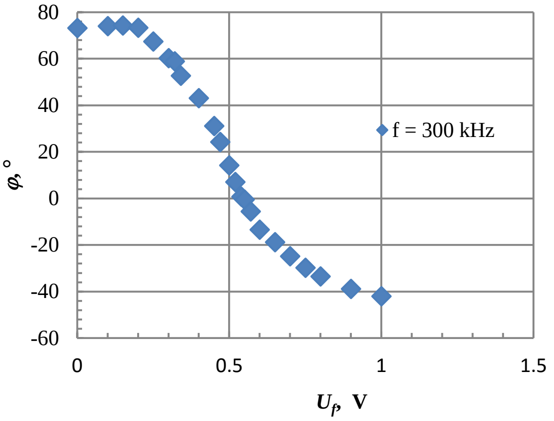

Figure 3. Dependence of phase shift angle between the current and voltage on the forward bias at f =300 kHz

Magnitude of negative capacitance C^- studied structures recalculated to inductance values at two frequencies (100 and 300 kHz) and at room temperature is represented in Figure 4. In this case the concentration of injected minority carriers varies by change of bias current within 0 up to 10 mA. From Figure 4 it is seen that with the rise of forward bias L being decreased sharply tends to the constant.

Maximum value $L \approx 50$ μH at U_f = 0.6 V. This value is considerably more than the magnitude of film planar inductances (helixes).

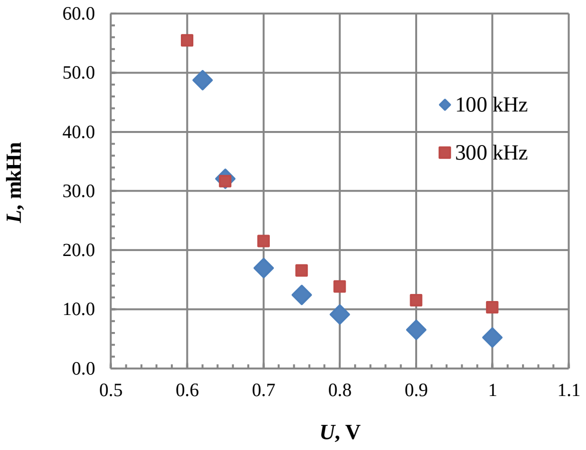

Figure 4. Dependence of inductance magnitude on the forward bias at two alternating signal 1÷100 kHz, 2÷300 kHz

To analyze obtained results there have been also investigated volt-ampere characteristics of MAPD structures (at room temperature T_r = 300 K). In Figure 5 there has been presented dependence of current on the forward bias in semilog scale for one of the typical samples. There has been observed exponential growth of current with the voltage

$$I_f = \text{const} \cdot \exp \frac{qU}{\beta_i kT} \tag{2}$$

where, the coefficient β_i determined from the slope of rectilinear part of characteristic $I_f(U_f)$ at room temperature within forward biases (0-0.5 V) is $\beta_i \sim 1.1$. Increasing U_f given dependence weakens and β_i takes on the value ~2.8.

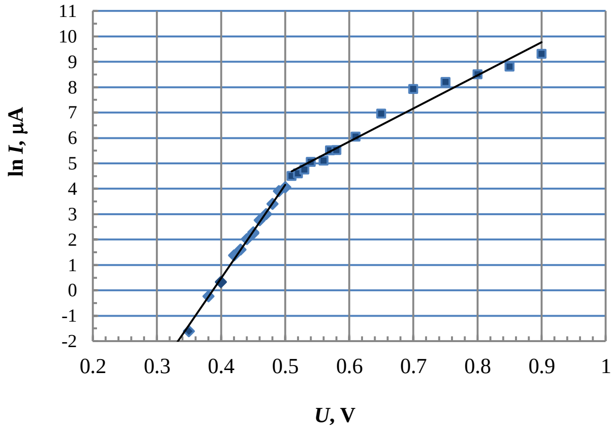

Figure 5. Forward branch of volt-ampere characteristics of micro-pixel avalanche photodiodes (MAPD-3N) at T_0 = 300 K (semi log scale)

As it is known by supply of forward bias on n-p junction if the width of space charge layer is less than diffusion bias length ($W \ll L_{p,n}$) the diffusion mechanism of current flowing [8] is taken place. In our case in spite of investigated structure involving three p-n junctions (in sections going through pixels) there has been obtained the first and second p-layers on epitaxial layer n^+Si by epitaxial method the diffusion mechanism of current flowing (at room temperature and $U_f < 0.5$ V) has been occurred.

The second slope in $\ln I_f / U_f$ dependence, observed at $U_f > 0.5$ V, where $\beta_i \sim 2.8$ as in Figure 5 appears to be related to the generation process in the space charge layer of the first p-n junction. Taking into consideration the detail design of the structures under investigation it is difficult to evaluate the contribution of each of three p-n junctions in total measured current and additional experimental investigations are needed that is the aim of further works.

V. CONCLUSION

It is shown that in silicon avalanche photodiodes with deeply buried pixels involving three p-n junctions by negative potential applied to n-Si substrate the capacitance rising by exponential low with forward bias changes the sign in the inversion point $U_f = U_{inv}$. The voltage of inversion does not depend on alternating signal frequency (f = 50÷300 kHz). The change of reactance sign is related to the change of initial Si substrate conductance due to the considerable increase of mobile carrier concentration within the first p-n junction. Maximum magnitude of negative capacitance recalculated to inductance value is 50 μH at $U_f = 0.6$ V and f = 100 kHz. Observed exponential growth of forward current with the voltage with coefficient $\beta_i \sim 1$ (at $U_f > 0.5$ V) is related to the diffusion mechanism of current flowing.

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BIOGRAPHIES

Elmira A. Jafarova was born in Nakhchivan, Azerbaijan, in June 1937. She graduated from Faculty of Physics, Moscow State University, Moscow, Russia in 1961. She received Ph.D. degree in Physics of Semiconductors and Dielectric from Institute of Physics, Azerbaijan National Academy of Science, Baku, Azerbaijan, in 1968 and Doctor of Physics and Mathematics Sciences degree in Physical Electronics, in 2007. Her publications are more than 150 articles and international conference proceedings including 40 in ISI/INSPEC indexed. Her research areas are transient electronic processes in multilayer silicon structures.

Ziraddin Y. Sadygov was born in Azerbaijan on March, 20, 1954. He received the M.Sc., Ph.D. and Doctor of Sciences degrees from Moscow Engineering Physics Institute (Moscow, Russia), all in Physics of Semiconductors and Dielectrics, in 1978, 1983, and 1997, respectively. Currently, he is the Leading Scientific employee at Institute of Physics (Baku, Azerbaijan) and the Chief Scientific employee at Joint Institute of Nuclear Research (Dubna, Russia). He has developed and patented three type of supersensitive micropixel avalanche photo diodes (MAPD) named also as silicon photo multipliers (SiPM) and microixel photon counters (MPPC).

Ali Huseyn A. Dovlatov was born in Baku, Azerbaijan, in July 1963. He received a five-year degree in Physics from the Azerbaijan State University, Baku, Azerbaijan in 1985 and the Ph.D. degree in Physics of Semiconductors and Dielectric from Institute of Physic, Azerbaijan National Academy of Science, Baku, Azerbaijan, in 2011. He has authored or coauthored of several papers (over to 25) in journals (including 6 in ISI/INSPEC indexed) and international conference proceedings. His current research interests are in area of designing and applications of high sensitive photo detectors and solar energy.

Zarifa A. Iskenderzade was born in Baku, Azerbaijan, in July 1935. She graduated from Faculty of Physics, Moscow State University, Moscow, Russia in 1959. She received Ph.D. degree in Physics of Semiconductors and Dielectric from Institute of Physics, Azerbaijan National Academy of Science, Baku, Azerbaijan, in 1965, and Doctor of Physics and Mathematics Sciences degree in Physical Electronics, in 1972. She is a Professor of Department of Electronics, Azerbaijan Technical University, Baku, Azerbaijan. She has authored or coauthored of several papers (over to 240) in journals (including 50 in ISI/INSPEC indexed) and international conference proceedings. Along with teaching she engaged in researches of physical processes in p-n junctions, hetero structures and photo converters.

Lala A. Aliyeva was born in Bolnisi, Faxraly, Georgia, in January 1960. She received a five-year degree in Physics from Azerbaijan State University, Baku, in 1981 and the Ph.D. degree in Physical Electronics from Institute of Physics, Azerbaijan National Academy of Science, Baku, Azerbaijan, in 2005. She has authored or coauthored of several papers (over to 20) in journals (including ISI/INSPEC indexed) and international conference proceedings. Her research interest is in photovoltaic converters.

Eldar S. Taptygov was born in Baku, Azerbaijan, in August 1946. He received a five-year degree in Computer Aided Manufacturing from Azerbaijan Institute of Oil and Chemistry, Baku, Azerbaijan, in 1971 and the Ph.D. degree of Physics and Mathematics Sciences in Physics of Semiconductors and Dielectric from Institute of Physics, Azerbaijan National Academy of Science, Baku, Azerbaijan, in 1988. He is an author of more than 50 papers in journals (10 in ISI/INSPEC indexed) and international conference proceedings. His research interests are in the area of porous and nanostructured surfaces.

Kamala A. Askerova was born in Nakchivan, Azerbaijan in September 1946. She graduated from Chemical Faculty, Azerbaijan State University, Baku, Azerbaijan in 1969. Her publications are more than 55 articles and international conference proceedings (including 30 in ISI/INSPEC indexed). She has two copyright certificates and one patent case. Her research interest is in photovoltaic converters.