Photoelectric properties of MIS structures on high-resistivity p-type silicon with aluminium nitride tunnelling insulator

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Abstract. Photoelectric properties of MIS tunnel diodes produced on high-resistive p-type silicon wafers with thin aluminium nitride AlN insulator layer and Pd or Al metal gate electrodes were investigated. It was found that synthesized AlN films possess a fixed positive charge, which leads to the creation of near-surface inversion layer in silicon substrate. The ratio of the photocurrent to the dark current $K = I_{ph} / I_{dark}$ (on / off ratio) was found to depend on the gate electrode material, illumination intensity and the applied reverse bias. For studied MIS structures $K$ ratio varied from $10^4$ to $10^5$ and was two orders of magnitude higher than that for the control MS structure without the insulator layer. High on / off ratio of such MIS structures with AlN tunnelling insulator promotes their application as an effective photodetectors in optoelectronics.

1. Introduction

Nowadays MIS (metal-insulator-semiconductor) structures with thin tunnelling dielectric layer are used as a basis of many semiconductor electronic devices: solar cells, field effect transistors, memory devices, etc. Therefore, the electrophysical and photoelectric properties of MIS structures produced on different semiconductors with various insulators were intensively investigated both theoretically and by experiments during past decades. Among others, various photoelectric effects were discovered [1-4], such as photocurrent multiplication or enhanced photosensitivity for non-transparent electrodes [5-6], when the photocurrent arises due to the carrier generation at the periphery of the gate electrode.

Several physical mechanisms explaining the effect of photocurrent multiplication were considered. In MIS structures with sufficiently thin insulator layer providing free carrier tunnelling the so-called “transistor” multiplication effect is realized, which consists in the difference of the majority and minority carrier tunnelling currents under the conditions of inversion band bending in the near surface region of semiconductor. With increase of the applied reverse bias, the photocurrent of the majority carriers exceeds the current of the minority carriers, what corresponds to the photocurrent multiplication [7-8]. In MIS structures with a thicker layer of insulator when tunneling probability is negligible, the photocurrent multiplication is associated with the formation of conducting channels in the dielectric under the light exposure and reverse bias application. In this case, the structures convert from a high-resistance state to a low-resistance state [9].
It should be noted, that most of previous investigations were performed on Al/SiO$_2$/n-Si structures with low-resistivity n-type substrates [2,8]. At the same time, photocurrent multiplication of MIS tunnel diodes made on high-resistivity silicon was not investigated previously. The advantages of this material are that the inversion layer in the near surface region could be created at considerably smaller applied reverse biases and, secondly, that it provides larger sensitive area with a smaller capacity as compared with a low-resistance substrate. It is however necessary to deposit an insulator layer by a low-temperature process in order to prevent the deterioration of the material quality. In this paper we present our first results of the investigations of photodetection properties of MIS tunnel diodes made on high-resistivity p-type Si substrates with thin aluminium nitride (AlN) insulator layer, which could be deposited at sufficiently low temperatures. This insulator material has a high dielectric constant $\varepsilon$=9 (as compared with $\varepsilon$=4 for silicon dioxide), excellent thermal, chemical and optical properties, high values of the breakdown electric field and provides satisfactory electrical quality of insulator-semiconductor interface [10]. Aim of the work was to clarify the role of the inversion layer on collection of photogenerated carriers and the influence of exciting light intensity on the photosensitivity of the investigated structures.

2. Samples and experimental details
Investigated MIS diodes were prepared on dislocation-free p-type (111) oriented Si wafers with a resistivity $\rho$ of 2500-4200 Ohm*cm and a minority carrier lifetime $\tau$ of about 1000-1200 $\mu$s. Polished wafers were etched in an HF : HNO$_3$ (1:8) solution and thoroughly washed in deionized water. Deposition of AlN films was carried out by reactive DC magnetron sputtering of an aluminium target in vacuum chamber pumped by oil-free system pumps. An argon/nitrogen (0.4/1.4) mixture of gases was used at the total pressure of 1.8*10$^{-3}$ mmHg. AlN film of 20-30 Å thickness was evaporated over the entire front area of the wafers, whereas the areas of Pd (500 Å) or Al (1000 Å) gate electrodes were essentially smaller than the total area of the wafer. The ohmic contact was made by the evaporation of Pd (500 Å) on the entire surface of the back side of the wafer.

The current-voltage (IV) and capacitance-voltage (CV) measurements were performed at room temperature in darkness and under illumination by LCR meter E7-20 by MNIPi. Illumination was performed by a tungsten light bulb and the intensity of illumination was regulated by changing the supply voltage. The temperature of the bulb filament was determined from the dependence of the metal resistance on temperature

$$R_T = R_0 (1 + \alpha(T - T_r)) = U/I$$

where $\alpha$ is the temperature coefficient of the metal (wolfram) resistance, $R_T$ is the filament resistance at the temperature $T$ corresponding to the current $I$ flowing through the filament under the application of the bias $U$, whereas resistance $R_0$ at room temperature $T_r$ was defined at a low supply voltage (~ 20 V) when the filament remains cold. Assuming that almost all of the electrical power is converted into the radiation power, the luminous flux in the absorption range of the Si substrate was estimated using the Planck formula accounting also for the solid angle of the illumination. Photocurrent experiments with collimated (by diaphragm) light flux directed on gate electrode showed that the contacts (Pd, Al) are partly transparent for light radiation.

3. Experimental results
3.1. Current-voltage measurements in darkness
The quality of prepared MIS structures was evaluated by their IV and CV characteristics measured in darkness. The reverse currents for MIS structures with Pd gate electrode did not exceed the value of few 10$^{-6}$ A (Fig. 1(a)) up to reverse bias of about 10 V, whereas with Al gate electrodes – up to the biases of about 100 V.
Low reverse dark currents imply the existence of high potential barrier at AlN/p-Si interface which the minority carriers – electrons have to overcome to get into the metal. Doping densities defined from the CV measurements corresponded to the expected substrate resistivity.

It should be noted also, that Pd being a metal with a high work function is usually applied as an ohmic contact to p-type silicon [11]. Therefore, in order to determine the magnitude, sign of the fixed charge in the deposited AlN films, as well as Pd/Si contact resistance, IV characteristics were measured in darkness on Pd/AlN/p-Si/Pd (structure 1, $\rho = 4.2 \, \text{kOhm cm}$, $\tau = 1 \, \text{ms}$, AlN film thickness $t_{\text{AlN}} \approx 20 \, \text{Å}$) and Pd/p-Si/Pd (structure 2, $\rho = 4.2 \, \text{kOhm cm}$, $\tau = 1 \, \text{ms}$) and the results are presented in Fig. 1 (a, b).

It is clearly seen in Fig. 1(a), that IV characteristic of structure 1 demonstrates the rectifying behaviour. For example – even at the bias voltages of 0.5 V the forward current exceeds the reverse one by 2 order of magnitude. In case of structure 2 without AlN film, the voltage dependence of the current was linear and almost symmetrical (Fig. 1(b)), giving a resistance of the p-Si/Pd ohmic contact as 430 Ohm.
Thus, comparison of two IV curves in Fig. 1 allowed us to conclude that the deposited AlN film possesses a fixed positive charge leading to creation of the rectifying contact at the Pd/AlN/p-Si interface. Knowing of the p-Si/Pd contact resistance and the flat bands voltage as defined from the forward branch of the IV curve we were able to determine the surface potential $\psi_s$ being equal to 0.32 eV. Obtained value of $\psi_s$ is considerably larger than the energy difference $\psi_v$ between the middle of the band gap and the Fermi level position in the neutral region of the substrate which was only 0.17 eV, indicating thus the presence of the inversion band bending in the near-surface region of the semiconductor [12].

### 3.2. Current-voltage measurements under illumination

Figure 2 represents the comparison of dark and illuminated IV curves measured on structure 1. First of all, it is worth noting that the reverse current on illuminated IV curve is considerably higher than the corresponding current measured in darkness. Besides, reverse photocurrent grows significantly with the applied reverse bias. The ratio $K$ of the maximal reverse photocurrent $I_{max}$ to the dark current $I_{dark}$ turned out to be around $10^4$. Additionally, the decrease of the photocurrent was observed at low forward biases from 0 V till -0.12 V (S-shaped or so-called photocurrent quenching effect), see Fig. 2(b).

Figures 3a and 3b (in logarithmic scale for a wider range of the reverse biases) show IV characteristics measured on MIS structure 3 ($\rho$=4.2 kOm*cm, $\tau$=1 ms, $t_{AlN}$ ~ 20 Å) with Al gate electrode at various values of the illumination intensity $P$. The values of the reverse photocurrent substantially increase with the magnitude of the light flux. At higher fluxes photocurrent grows continuously with the reverse bias (curves 3 and 4 in Fig. 3(b)), whereas at low fluxes reverse photocurrent saturates (curve 1 in Fig. 3(a) and curves 1 and 2 in Fig. 3(b)). Since the value of the dark current remains constant and nearly bias independent, the result obtained means that $K = I_{ph} / I_{dark}$ increases with the magnitude of the light flux. It should be noted also, that the value of the short-circuit photocurrent $I_{sc}$ as well as forward branches of the IV curves measured under illumination do not vary significantly with the light intensity (Fig. 3(a)).

![Figure 3](image-url)

**Figure 3.** (a) IV curves of Al/AlN/p-Si/Pd structure 3 measured under illumination with different light fluxes $P$: 1 – $P = 0.8$ mW/cm², 2 – $P = 3$ mW/cm², 3 – $P = 15$ mW/cm². (b) Reverse branches of IV curves measured on the same structure 3 under illumination with fluxes $P$: 1 – $P = 1.8$ mW/cm², 2 – $P = 4$ mW/cm², 3 – $P = 15$ mW/cm², 4 – $P = 73$ mW/cm².
Figure 4 demonstrates the comparison of the reverse branches of IV curves measured under illumination on MIS structure 4 ($\rho = 2.5$ kOm·cm, $\tau = 1.2$ ms, $t_{\text{AlN}} \sim 30$ Å) with Al gate electrode and metal-semiconductor (MS) Al/p-Si/Pd structure 5 prepared on the same wafer as structure 4 but without the layer of AlN insulator. At low reverse biases reverse photocurrent on structure 5 is higher than photocurrent on structure 4, implying thus that the potential barrier at AlN/p-Si interface which the minority photogenerated electrons have to overcome to get into the metal is higher than that at Al/p-Si interface of metal-semiconductor contact. Whereas at the reverse biases above 2.5V reverse photocurrent on MIS structure becomes higher than the photocurrent on MS structure, what indicates on the presence of separate mechanism of photocurrent multiplication in MIS structures. Comparison of the reverse currents measured in darkness and under illumination in Fig. 4 gives the photocurrent to dark current ratio $K$ on MIS structure 4 of about $10^3$ as compared with only $10^3$ on MS structure 5.

![Figure 4](image_url)

**Figure 4.** Reverse branches of IV curves of Al/AlN/p-Si/Pd structure 4 measured under illumination (curve 1) and in darkness (curve 4, multiplied by factor of 2000) and of Al/p-Si/Pd structure 5 measured under illumination (curve 2) and in darkness (curve 3, multiplied by factor of 1000).

4. Discussion

As it was mentioned above, the evaporated Pd and Al gate electrode layers transmitted only a small part of light irradiation. Under illumination considerable reflection and absorption of light by gate electrodes causes a strong gradient of photogenerated carriers in radial direction (i.e. towards the metal electrode from the outside areas). Existing surface conductive channel and a strong electric field at semiconductor/insulator interface near the metal electrode edges (the so-called halo [13]) appearing at high reverse biases both ensure the drift and diffusion of nonequilibrium minority electrons towards the contact region and draw them into a potential well under the gate electrode. At AlN/p-Si interface, as it was seen from the reverse branch of dark IV characteristics (Fig. 1(a)), there is a significant potential barrier for electrons that prevents their transition towards the metal. Presence of the potential barrier for electrons at AlN/p-Si interface promotes accumulation of the photoelectrons in the well, thus increasing the negative charge density at the interface and, as a consequence, the electric field in the insulator. This leads to an increase of photocurrent due to the potential barriers lowering for both the electrons tunneling into the metal and the holes injected from the metal electrode. As a result, a significant dependence of the reverse photocurrent magnitude on the applied bias and illumination intensity is observed for MIS structures.

When forward bias is applied, the halo of the electric field around the metal contact narrows, carrier recombination rate increases as more holes coming closer to the interface. Additionally, back diffusion of electrons from the surface towards the bulk will take place [14]. The recombined or diffused into the bulk photoelectrons, naturally, do not contribute to the photocurrent, therefore its value decreases. As forward bias increase, the processes of surface recombination and back diffusion of electrons into the bulk intensify, what leads to the photocurrent suppression as it could be seen in Fig. 2(b). At forward biases above the open circuit voltage $V_{\text{oc}}$ the MIS structure under illumination behaves like a regular photodiode.
5. Conclusions
MIS structures based on high-resistivity p-type silicon with aluminium nitride tunnelling insulator were investigated. A distinctive feature of the investigated structures is the large positive charge in the AlN insulator film which leads to the creation of the near-surface inversion layer. Diffusion and drifting of minority light-generated carriers in this conductive surface channel together with the lowering of the potential barrier for carrier tunnelling could be the possible mechanisms of the photocurrent enhancement in such MIS structures with weakly transparent metal electrodes. High photocurrent to dark current ratio and ease of manufacture makes such structures a promising candidate for optical sensor applications where high irradiance responsivity and low-cost fabrication are desired.

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References
[1] Chu K M, Pulfrey D I 1988 IEEE Transactions on Electron Devices ED-35 188
[2] Vul’ A Ya, Dideikin A T et al 1992 Fizika i Tekhnika Poluprokovodnikov 26(2) 295
[3] Chu-Hsuan Lin and Chee Wee Liu 2010 Sensors 10 8797
[4] Chu-Hsuan Lin, Wei Ting Yeh, Chun-Hui Chun and Chun-Chieh Lin 2012 Nanoscale Research Letters 7 343
[5] Jen-Yan Cheng, Hui-Ting Lu, and Jenn-Gwo Hwu 2010 Appl.Phys.Lett. 96 233806
[6] Liu C W, Liu W T, Lee M H 2000 IEEE Electron device Letter 21 307
[7] Grekhov I V, Veksler M I, Ivanov P A, Samsonova T P, Shulekin A F 1998 Semiconductors 32 1024
[8] Slobodchikov S V, Kovalevskaia G G et al 1993 Fizika i Tekhnika Poluprokovodnikov 27(7) 1213
[9] Rozhkov V A, Shalimova M B 1999 Semiconductors 33 731
[10] A.Chespi, and J.Millon 2010 Science 604(1) 63-67
[11] Avdeichikov V 1978 NIM 155 125
[12] Sze S M 1981 Physics of Semiconductor Devices John Wiley & Sons, New York
[13] Torkhov N A, Novikov V A 2011 Semiconductors 45 69
[14] Ng K K and Card H C 1980 J.Appl.Phys. 51 2153