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ITO/SiO_x/Si optical sensor with internal gain

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Abstract

A visible/near-infrared optical sensor based on an ITO/SiO_x/n-Si structure with internal gain is presented. This surface-barrier structure was fabricated by a low-temperature processing technique. The interface properties and carrier transport were investigated from dark current–voltage and capacitance–voltage characteristics. Examination of the multiplication properties was performed under different light excitation and reverse bias conditions. The spectral and pulse response characteristics are analysed. The current amplification mechanism is interpreted by the control of electron current by the space charge of photogenerated holes near the SiO_x/Si interface. The optical sensor output characteristics and some possible device applications are presented.

Keywords: Optical sensor; Silicon; Indium–tin-oxide films; Photocurrent multiplication

1. Introduction

Surface-barrier Si-based photodetectors exhibit attractive features such as high quantum efficiency, uniform sensitivity over the entire active area, and above all simplicity in design and fabrication. The junction is usually formed by deposition of a sufficiently thin metal layer or metal oxide film onto an etched semiconductor surface [1]. If an insulating layer is inserted between the top electrode and the semiconductor, photocurrent multiplication can be obtained [2–4]. The multiplication process is related to the carrier transport through the insulator layer. Two different mechanisms can be responsible for the photocurrent multiplication effect.

The first type of devices are MIS and SIS tunnel diodes, the charge carriers can tunnel freely thorough the sufficiently thin insulator layer (less then 50 Å for the SiO_2/Si interface). In this case the photocurrent amplification has been explained by a redistribution of the semiconductor and insulator energy bands with respect to the metal Fermi level, when the external injection creates an inversion layer at the semiconductor surface [2].

At the same time, high internal current gains have been achieved in structures with thicker oxide layers, where direct tunnelling of charge carriers is negligible [3,4]. The conductivity of such structures is caused by the formation of conductive channels through the porous silicon oxide layer. These conductive paths connect the small size quasi-ohmic contacts formed on the semiconductor surface with the top electrode. Under illumination the minority carriers fill the potential well at the semiconductor surface and the depletion width decreases causing a significant increase of contact conductivity and device current. We have fabricated such structures in order to investigate device features and to develop a low-temperature processing technique for production of high quantum efficiency and low-cost optical sensors with internal current gain. In Section 2 the theoretical basis is presented, following sections give some details about device preparation and characterisation with discussion of results.

2. Photocurrent multiplication mechanism

To explain the multiplication properties of the ITO/SiO_x/n-Si structures we will use the carrier transport mechanism for a MOS capacitor with a multichannel insulator, as proposed in [4]. According to this model, the photocurrent multiplication phenomena is a result of the formation of conductive paths through the porous silicon oxide layer, which connect the small size ohmic contacts formed on the semiconductor surface with the top electrode. A cross-section of a structure with such a contact is schematically represented in Fig. 1.

If reverse voltage is applied, an electron current will flow from the top to the back contact through a conductive channel. The channel length and cross-section is determined by the edge of the depletion region.

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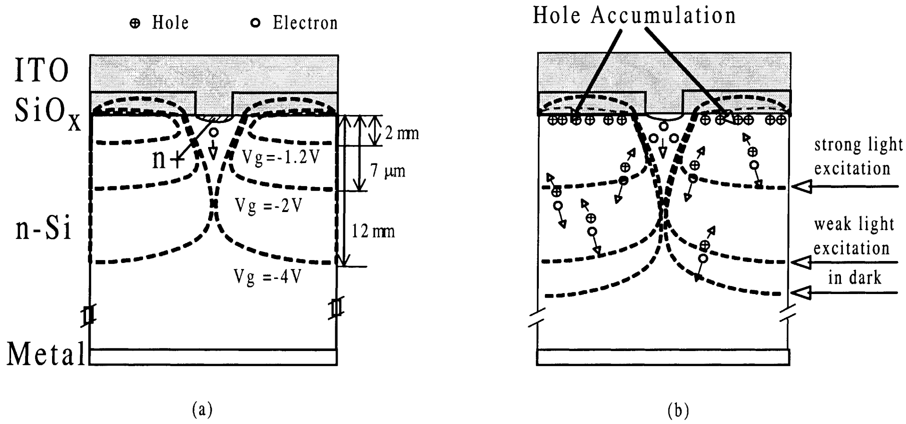

Fig. 1. Schematic representation of the carrier transport mechanism in a reverse biased ITO/SiO_x/Si structure in: (a) dark and (b) under illumination. The dashed lines represent depletion region edge.

Thus, both the applied voltage and the accumulated space charge of holes near the SiO_x/Si interface control the current. If the applied voltage is high enough, the depletion layer width can exceed the average channel diameter causing a current saturation, as shown in Fig. 1(a).

Under illumination, the photogenerated holes are collected in the potential well on the SiO_x/Si interface and the depletion width decreases causing an increase of the channel conductivity.

As shown in Fig. 1(b), at weak light excitation the depletion region reduction is not enough for a considerable current increase. For strong light excitation the photocurrent increase is significant due to a depletion region width comparable with the average channel size. For this reason some level of additional steady-state illumination is necessary to enhance the dynamic photoresponse.

3. Experimental details

The devices under this study were fabricated using ⟨1 0 0⟩ oriented n-type silicon crystalline substrates having a resistivity of 140–1000 Ω cm. The oxide layers with thicknesses of 8–12 nm were grown on the substrates by thermal oxidation in air at 673 K. The circular top indium–tin-oxide contacts having a thickness of 70 nm and a 2.5 mm diameter were formed by reactive thermal evaporation at a low substrate temperature ($383\,K < T_s < 473\,K$). This layer acts as an effective collector of the photogenerated carriers and, simultaneously, as an antireflection coating. To ensure a good ohmic contact a 50 nm Cr/300 nm Al bilayer was deposited on the n^+ backside diffusion.

In order to characterise the fabricated devices, electrical and optical measurements were performed. Current–voltage characteristics (*I–V*) in dark and under different illumination conditions were obtained at room temperature. *C–V* measurements were carried out with a 10^5 Hz/20 mV test signal, using a lock-in amplifier to measure real and imaginary part of the ac impedance. Sample capacitance and conductance were evaluated from the measured values, assuming a parallel *RC* model.

The spectral characterisation in the range of 0.35–1.1 μm was performed using the lock-in technique with a chopper frequency of 78 Hz.

4. Results and discussion

4.1. I–V and C–V characteristics

Fig. 2 shows the dark *I–V* characteristic of a device with internal gain. The presence of a non-ideal insulator layer permits the current flow through the structure in both reverse and forward bias conditions.

Under reverse bias the *I–V* characteristics show two main regions. A first one, where the reverse current increases linearly with the applied bias (linear region) due to the effect of parallel shunt paths through the SiO_2 film, and a second one, where the current saturates (saturation region).

The *C–V* characteristics shown in Fig. 3 correlate well with the behaviour of the reverse *I–V* characteristic. At small reverse bias the device behaves as a MOS capacitor. In the saturation region, the linear relationship between $1/C^2$ and V corresponds to a p–n junction behaviour due to surface charge draining [5]. The *C–V* curve of an ITO/n-Si Schottky

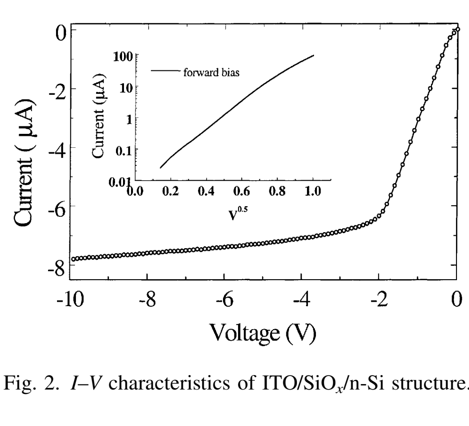

Fig. 2. *I–V* characteristics of ITO/SiO_x/n-Si structure.

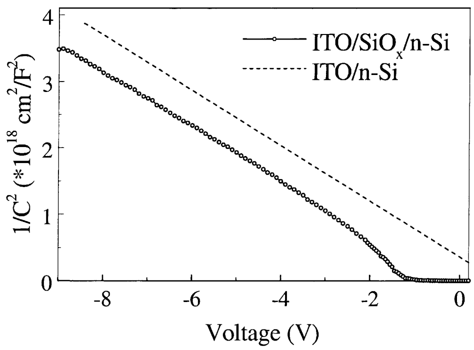

Fig. 3. C–V characteristics of ITO/SiO$_x$/n-Si structure.

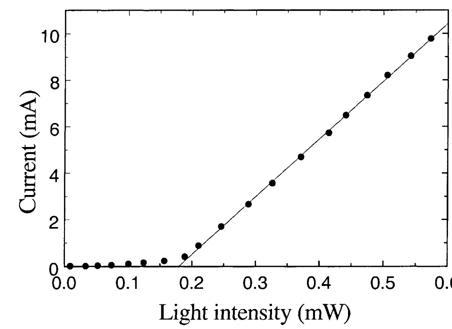

Fig. 5. Photocurrent vs. intensity of incident light at $\lambda = 0.633$ μm and -7 V bias.

diode calculated for a donor concentration $N_D = 3\times 10^{13}$ cm^{-3} and barrier height $\phi_b = 0.887$ eV is shown for comparison (dashed line Fig. 3) [1].

4.2. The optical sensor properties

Fig. 4 shows the current and conductance $G = dI/dV$ as functions of voltage for the ITO/SiO$_x$/n-Si structure with high internal gain under steady-state illumination. The photocurrent multiplication was detected at reverse voltage greater than 0.9 V. In contrast with dark the I–V characteristic, the photocurrent–voltage relationship follows a quadratic dependence in the interval 0.9–1.8 V reverse bias and the photocurrent saturates at higher voltages. The maximum of conductance (dashed line in Fig. 4) is observed approximately at -2 V bias, this value corresponds to the transition region of the dark I–V curve.

Fig. 5 shows the relationship between the photocurrent and intensity of incident light at -7 V bias. The device switches to a high gain mode at current $I_s \approx 0.4$ mA. A linear slope $dI/dP = 25$ A/W is observed when the light intensity overcomes the threshold value $P_s \approx 0.2$ mW (or radiation flux ≈ 4.1 mW/cm^2) at $\lambda = 0.633$ μm.

One can expect that the dynamic response should depend on the steady-state illumination conditions. If the intensity of the modulated light is less than P_s for a given wavelength, the output signal will be increased by additional light excitation. Under a 1.4 ms light pulse from a LED

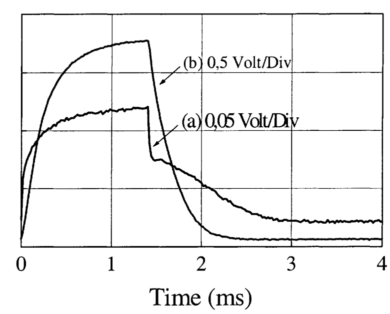

Fig. 6. The response waveform characteristics: (a) without and (b) with additional background illumination at -9 V bias. The square-wave modulated light has an intensity of 5×10^{-5} W at $\lambda = 0.875$ μm.

($\lambda = 0.875$ μm), the amplitude of the current pulse is increased more than 10 times by steady-state illumination from a tungsten lamp as shown in Fig. 6. The dc current caused by the steady-state irradiation was about 1 mA. The slow current decay without additional background illumination (Fig. 6 (a)) seems to be caused by an accumulation of photogenerated holes at the SiO$_x$/Si interface. The response time goes down to 0.4 ms with additional light excitation.

Fig. 7 shows the small signal spectral responsivity of the optical sensor in the high gain mode obtained under -7 V bias and background illumination from a wide spectral range light source. The spectral characteristic has a shape similar to the one of a blue enhanced silicon photodiode but with a

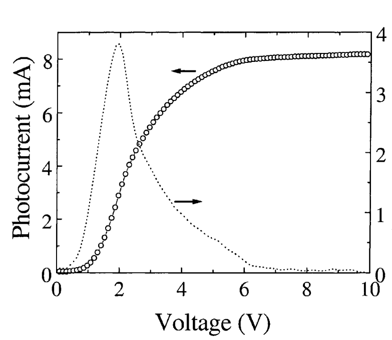

Fig. 4. Photocurrent and conductance (dashed line) vs. reverse bias voltage under a light intensity of 5×10^{-4} W at $\lambda = 0.633$ μm.

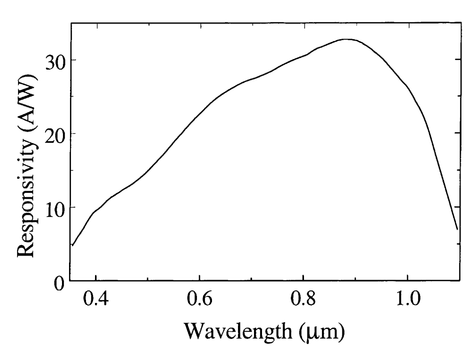

Fig. 7. The small signal spectral responsivity at -7 V bias and white light background illumination from a wide spectral range tungsten lamp.

much higher responsivity. The maximum responsivity (32.8 A/W) is observed at λ=0.88 μm, this is about 50 times larger than the responsivity of conventional photodiodes.

5. Conclusions

Photocurrent multiplication effect has been observed in ITO/SiO_x/n-Si structures under reversed bias. The effect of the bias condition, the intensity of incident light and the additional background illumination on the photocurrent has been investigated. The current amplification mechanism has been interpreted by the control of the electron current by the space charge of photogenerated holes near the SiO_x/Si interface.

The internal gain observed in ITO/SiO_x/n-Si structures makes this type of optical sensor a promising candidate for applications where high responsitivity and low-cost devices are desired. Typical applications include photoelectric control, position monitoring, triggering circuits, and image sensors.

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Biographies

Miguel Fernandes was born in Portugal in 1970. In 1993 he became researcher in the Center of Excellence for Microelectronics and Optoelectronics Processes-UNINOVA, Lisbon, Portugal. He graduated in Physics and Materials engineering by the Faculty of Sciences and Technology from the New University of Lisbon in 1995. Currently he is Assistant Professor in Electronics Department of ISEL, Lisbon, Portugal and investigator in the group of Applied Research in Microelectronic Optoelectronic and Sensors-GIAMOS in the same institution.

Yuri Vygranenko was born in Ukraine in 1963. He received the degree in Physics by the Chernovtsy University, Ukraine in 1985. Between 1985 and 1987 he worked as engineer at the optoelectronics device plant "Quartz", Ukraine. Later he became scientific collaborator in the Chernovtsy Department of the Institute of Materials Science Problems, where his research work was related to the physics and technology of the IV–VI narrow-gap semiconductors. In 1997 he received his PhD in Physics from the Chernovtsy University. Currently he works as researcher in ISEL, Lisbon, Portugal.

Reinhard Schwarz was born in Großköris, Germany in 1950. He received the degree in Physics and Mathematics by the University of Stuttgart, Germany in 1977. He joined the Department of Physics in Neuchâtel University, Switzerland where he was teacher and where he received his PhD in 1982. After this date he became scientific collaborator in the Institute of Microtechnology, University of Neuchâtel, Switzerland until 1983 when he joined the group of Prof. S. Wagner in the Department of Electrical Engineering, Princeton University, USA. Later he joined the Physics Department E16 of Technische Universität München, Germany until 1996. Since then he teaches as Invited Professor in the Physics Department in Instituto Superior Técnico, Lisbon, Portugal and Coordinator Professor in Electronics Department of Instituto Superior de Engenharia de Lisboa, Portugal.

Manuela Vieira was born in Lisbon, Portugal in 1951. She graduated in Physics by the Faculty of Science of the University of Lisbon in 1974. In 1986 received the Master of Science in Solid State Physics Microelectronic by the New University of Lisbon. At that time she became Auxiliary Professor of Semiconductor and Microelectronics in ISEL, Lisbon where she is now Coordinator Professor in Semiconductor/Electronics and President of the Department of Electronics and Communications. In 1984 she became member of Center of Excellence for Microelectronics and Optoelectronics Processes-UNINOVA, Portugal. In 1993 she received the PhD in Semiconductor Materials from the New University of Lisbon. Currently she is the head of the Group In Applied Research in Microelectronic Optoelectronic and Sensors-GIAMOS/ISEL in Lisbon, Portugal. Dr M. Vieira has several scientific papers and more than 12 years of experience in the field of thin films and devices, her research activities have been mainly related to the transient analysis and characterisation of the transport properties of the semiconductor materials and device characterisation.