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Integrated Optoelectronic Unit Based on Porous Silicon

S. Lazarouk, P. Jaguiro, and V. Borisenko

Belarussian State University of Informatics and Radioelectronics, P. Browka 6, 220 600 Minsk, Belarus

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An original device design including an aluminum–porous silicon light emitting diode connected with a photodetector by an alumina waveguide has been developed. Distinct photoconductivity and photovoltaic effects have been clearly revealed from current–voltage curves of the photodetector. The comparison of external light excitation and internal light excitation has shown that photoresponse is considerably higher in case of the internal light source. Furthermore, the photoresponse from the internal light source can be increased by using a special reflector film along the edge of the aluminum electrode. The presented optoelectronic unit has been made by silicon technology and can be used for high speed optical interconnects within VLSI-IC.

1. Introduction

Porous silicon (PS) is considered to be a promising material for optoelectronic applications. Under optical or electrical excitation this material produces strong visible light emission. It can be fabricated using a relatively simple and inexpensive electrochemical technique that is easily integrated with the existing silicon technology. We already reported on light emitting diodes (LED) based on aluminum–PS reverse biased Schottky junction [1, 2]. There were some attempts to combine PS LED with silicon electronic and optoelectronic components. In [3] PS based LED integrated into microelectronic circuits has been presented. In [4] PS LED with a silicon based optical cavity has been fabricated. In this paper we present the design and performance of a silicon integrated optoelectronic unit based on porous silicon for light emission and on alumina film for light waveguiding.

2. Design and Technological Steps

A schematic cross-section of the developed silicon integrated unit is shown in Fig. 1. It includes two aluminum–PS Schottky junctions, an alumina layer between them, and a niobium mask on the surface of the aluminum electrodes. One of the junctions operates as a LED, another as a photodetector (PD). The distance between them is 20 μm. The anodic aluminum oxide (alumina) protects the porous silicon surface from atmospheric oxygen. Moreover, it plays another important role in the device. The light emitted by one of the Schottky junctions is transmitted in the alumina layer as in an optical waveguide. As far as the refractive index of porous silicon (1.3 to 1.6) is lower than that of alumina (1.65 to 1.77) [5], the anodic alumina layer provides an appropriate light guiding effect.

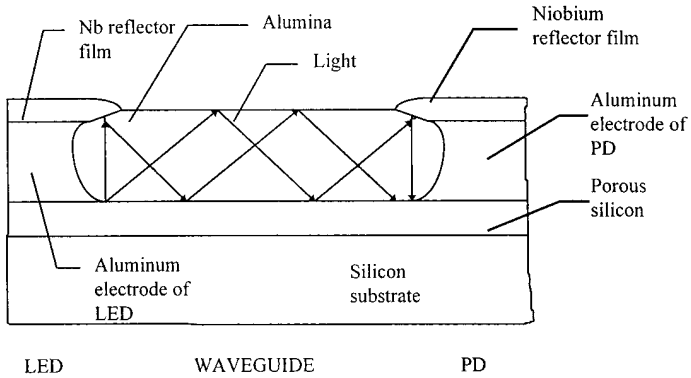

Fig. 1. Schematic diagram of the developed optoelectronic unit

The upper niobium film is employed for two purposes. First of all it is used as a mask for selective anodization of aluminum. For that the width of the niobium mask shall be higher than that of the aluminum electrode accounting for the undercutting effect taking place during the anodization [6]. Undercutting is regulated by choosing of the anodization time. The second is that the niobium film acts as a reflector which confines light spreading in the anodic alumina layer, as demonstrated in Fig. 1. At visual control of light emission we observed light the brightness along the edges of the aluminum electrodes to be considerably reduced with respect to similar devices without the niobium mask. It means that the emitted light mostly propagates inside the alumina layer due to the reflection from the niobium film.

The LED and the PD are designed on the basis of identical Schottky junctions between the aluminum electrodes and PS. At a reverse bias below the breakdown voltage the Schottky diode operates as a PD, while near the breakdown it performs as a LED.

The photodetector can also operate in the photovoltaic regime at zero bias as a solar cell [7], but the reverse bias regime is more attractive. First, it possesses the electric insulation of the device from the semiconductor substrate by the reverse biased junction. Second, the reverse bias increases considerably the frequency response of the PD due to reduction of the carrier transit time and junction capacitance [8]. However, the maximum bias is limited by the breakdown effect which results in microplasmas with intrinsic light emission [1]. Therefore, in our optoelectronic system the PD operates as a Schottky diode with a depletion region. In this case the reverse bias current is modulated by electron–hole pair generation in the depletion region by light absorption.

The main technological steps for the production of the described optoelectronic unit were focused on the formation of the LED [1]. Silicon wafers of 0.01 to 0.1 Ω cm, n-type with (100) orientation were used as substrates. The porous silicon layer was formed in a transition anodization regime [9] in 1% HF aqueous solution, with a current density of 4 mA/cm^2. The thickness of the layer was about 1 μm. An aluminum film of 1 μm thick was deposited by magnetron sputtering on top of the PS layer.

After that the silicon wafers were divided into two parts to produce optoelectronic units with and without the niobium film mask. In the first group the photoresist mask was fabricated by standard photolithography operations. This mask was used for aluminum local anodization. It was performed in 5% aqueous oxalic solution in the potentio-

static regime at a forming voltage of 45 V for 20 min. After anodization the photoresist mask was removed. In the second group of samples a niobium film of 0.3 μm thick was deposited on the aluminum film by magnetron sputtering. After that the niobium mask was formed by photolithography and plasma etching as was described in [6]. The niobium mask was used for aluminum local anodization, which was performed in the same regime as for the first group. Thus, the two structures differ by the presence of the niobium reflector film.

3. Results and Discussion

Current–voltage characteristics of the Schottky diodes have been measured in dark and at different levels of illumination by incoherent light. Fig. 2 shows the relation of the light current to the dark one as a function of the reverse bias for the PD diodes. The devices can operate in the voltage range of 0.2 to 2 V. In case of higher reverse voltage the photoresponse from the external light is significantly decreased by intrinsic light emission related to microplasmas resulting from avalanche breakdown effects. For such diodes this effect has been observed in [1] to become valuable above 2.5 V. Moreover, the applied voltage is a breakdown limit for electric insulation of the diode.

Light emission from the LED was registered by the integrated PD, when the LED was biased with 5 V and higher. Fig. 3 demonstrates the relation of the light current to the dark one as a function of the LED reverse voltage. Comparison of the data from Fig. 2 and 3 shows the photoresponse to be considerably higher in the case of light emission from the LED. It can be explained by the lower distance between the light source and the photodetector, and also by the waveguide effect in the alumina film. Moreover, the photoresponse from the adjacent LED can be increased by the niobium reflector film (curve with solid squares in Fig. 3). It should be noted, that some light can go via the PS layer, but this part of light is insignificant, because the refractive index of PS is lower than that of alumina.

Unfortunately, we were unable to estimate the time response of the integrated optoelectronic unit produced. The reason is that electric insulation between the LED and PD is realized by the reverse biased Schottky junction. This kind of insulation is effective for low frequency signals, but for high frequency ones the electric current can pass through the Schottky barrier capacitance. Therefore, for high frequency measurements we should use an additional electric insulation. The time response estimated by separate measurements of this parameter for the LED and PD is a few nanoseconds [1]. In case of reliable high frequency electric insulation between the LED and PD we expect the time response for the developed optoelectronic unit to be in the nanosecond range, while it can be further improved by the optimization of the design and the technology.

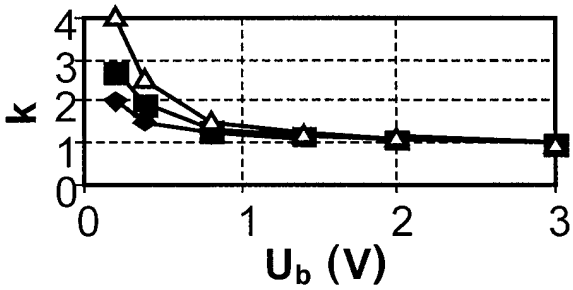

Fig. 2. Light to dark current as a function of photodetector reverse voltage for various values of external light: 10 (◆), 50 (■), 100 mW/cm^2 (△)

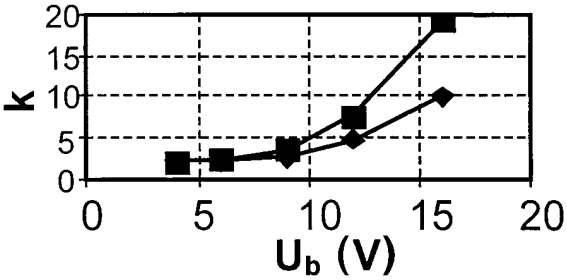

Fig. 3. Light to dark current as a function of LED voltage for different structures: LED connecting with the photodetector by the alumina waveguide (◆), LED connecting with the photodetector by the alumina waveguide and the reflector film (■)

4. Conclusion

We have designed and developed the technology for an all silicon integrated optoelectronic unit for high speed optical interconnections in integrated circuits. It includes a porous silicon based light emitting diode connected with the photodetector by an alumina waveguide partially covered by a niobium reflector film. Therefore, this work opens new possibilities for integration of electronic and optoelectronic devices.

References

[1] S. Lazarouk, P. Jaguiro, S. Katsouba, G. Masini, S. La Monica, G. Maiello, and A. Ferrari, Appl. Phys. Lett. **68**, 2108 (1996).
[2] S. Lazarouk, P. Jaguiro, S. Katsouba, S. La Monica, G. Maiello, G. Masini, and A. Ferrari, Thin Solid Film **276**, 168 (1996).
[3] K. D. Hirschman, L. Tsybeskov, S. P. Duttagupta, and P. M. Fauchet, Nature **384**, 338 (1996).
[4] M. Araki, H. Koyama, and N. Koshida, Appl. Phys. Lett. **69**, 2956 (1996).
[5] G. V. Samsonov, Physico-Chemical Oxide Properties, Izd. Metallurgia, Moscow 1978 (in Russian).
[6] S. Lazarouk, I. Baranov, G. Maiello, G. De Cesare, and A. Ferrari, J. Electrochem. Soc. **141**, 2556 (1994).
[7] S. La Monica, G. Maiello, A. Ferrari, G. Masini, S. Lazarouk, P. Jaguiro, and S. Katsouba, Thin Solid Film (1997), to be published.
[8] S. M. Sze, Semiconductor Devices: Physics and Technology, Bell Tel. Lab., Inc., New York 1985.
[9] M. Bertolotti, F. Carassiti, E. Fazio, A. Ferrari, S. La Monica, S. Lazarouk, G. Liakhou, G. Maiello, E. Proverbio, and L. Scirone, Thin Solid Film **255**, 152 (1995).