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Reverse biased porous silicon light-emitting diodes for optical intra-chip interconnects

S.K. Lazarouk*, P.V. Jaguiro, A.A. Leshok, V.E. Borisenko

Belarusian State University of Informatics and Radioelectronics, P. Browka 6, Minsk 220013, Byelorussia

Abstract

We have reported recent progress in development of the integrated optoelectronic unit on a Si chip. The developed optoelectronic unit includes a porous Si light-emitting diode (LED) connected with a photodetector by an alumina waveguide. Main attention has been devoted to the enhancement of LED parameters. Quantum efficiency as high as 0.4% has been reached. The delay time of 1.2 ns and the rise time of 1.5 ns have been measured for the diodes. Further improvements are also discussed.

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Keywords: Light-emitting diode; Photodetector; Porous silicon; Alumina waveguide

1. Introduction

Recent developments in communication systems and computer technology make increasingly attractive the substitution of electrons with photons in transmission and processing of information. Thus, optoelectronic interconnects are required for the next generation of integrated systems. Since the discover of an efficient light emission from porous silicon, this material is considered to be promising for integrated silicon-based optoelectronic systems able to emit, transmit, and detect light in the visible range.

We reported on an aluminum/porous silicon junction, which operates like a light-emitting diode (LED) when biased above the avalanche breakdown [1], and on an integrated optoelectronic unit including the porous silicon LED connected with a photodetector (PD) by an alumina waveguide [2,3]. The developed avalanche LED can be integrated with conventional CMOS silicon devices in the same chip. In this paper, we present recent extended data characterizing operation of the integrated optoelectronic unit with the avalanche porous silicon LED.

2. Experimental

The main technological steps of fabrication of the integrated optoelectronic unit are described in Ref. [3]. An equivalent scheme of the developed silicon integrated optoelectronic unit is shown in Fig. 1 helps understanding the device performance. The unit includes two aluminum/porous silicon Schottky junctions, an alumina layer between them arranged like it is schematically shown in Fig. 1. One of the

* Corresponding author. Tel.: +375-17-239-88-69; fax: +375-17-231-09-14.

E-mail address: serg@nano.bsuir.edu.by (S.K. Lazarouk).

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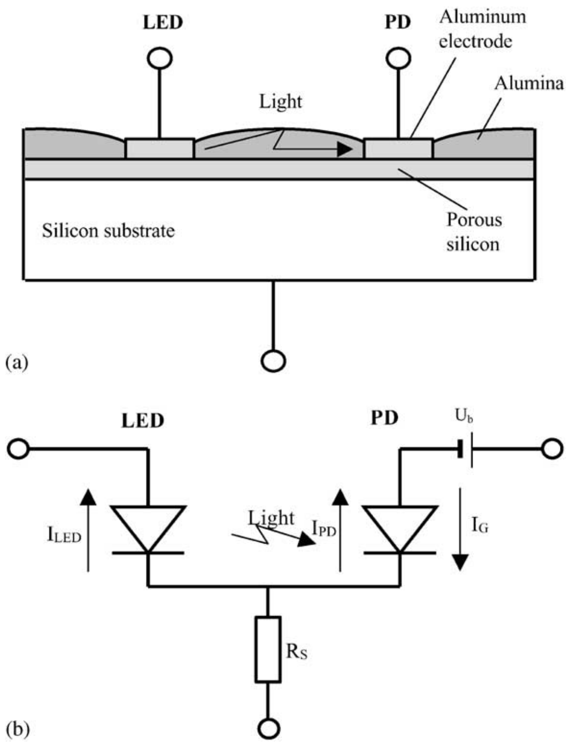

Fig. 1. Schematic diagram of integrated porous silicon optoelectronic unit (a) and its equivalent electric scheme (b).

junctions operates as a LED, another as a PD. The distance between them is 7 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 within the alumina layer as in an optical waveguide. As far as the refractive index of porous silicon (1.3–1.6) is lower than that of alumina (1.65–1.77) [2], the anodic alumina layer provides an appropriate light guiding effect.

The fabricated devices were characterized with time response, transient electroluminescence and delay time techniques. The time response of the avalanche LEDs was measured when the device was biased with a short pulse generator (E1-14). The emitted light passing through a monochromator was detected by a fast photomultiplier. The current through the device was in the range of 10–240 mA. The transient electroluminescence was recorded between the leading and trailing edges of the current pulse measured at 10% and 90% of the current amplitude corresponding to 1.0 ns, which are dominated by RC time constant of the pulse generator. The delay time was measured by comparison of the recorded transient characteristics with a transient characteristic of the reference tunnel GaAs LED, which had the delay time less than 0.1ns.

3. Results and discussion

Light is generated when the left Schottky junction is biased by a voltage close to the avalanche breakdown and reverse current (I_{LED}) passes through it. Meantime reverse current appears in the right Schottky junction operating in a PD mode. The current through this junction is experimentally recorded to increase with an increase of I_{LED} as it is depicted in Fig. 2. The similar behavior is observed for an external light irradiation of this junction. So, we conclude that the measured current is a photo response of the right Schottky junction.

There is a galvanic link between the LED and the PD (see Fig. 1). However, the direction of the galvanic current (I_G) is opposite to the measured PD current (I_{PD}). In order to reduce the influence of the galvanic current, we have used an additional batteries of 1.5–3 V connected with the PD, as it is shown in the Fig. 1. Moreover, the substrate resistance (R_S) is about 10 Ω, and simple calculation shows, that for I_{LED} less than 100 mA the I_G could not change the PD bias. But for the I_{LED} above this value the I_G affects the PD bias, thus resulting in the decrease of the I_{PD} values. The increase of I_{LED} can even change the polarity of I_{PD} due to inversion of the net PD voltage. It is obvious that this effect takes place for various battery biases at different I_{LED} values, as shown in Fig. 2.

The relationship between I_{PD} and I_{LED} is close to quadratic dependence. Meantime, the relationship between LED electroluminescence and I_{LED} is also quadratic [5]. It confirms that the PD response originates from LED light emission.

The ratio of I_{PD} to I_{LED} reaches 0.4%. This value can be considered as a quantum efficiency of the LED. The external quantum efficiency measured by an external PD was one order less. It means, that the light from the integrated LED mostly propagates through the alumina waveguide in the horizontal direction. It should be noted that the developed optoelectronic unit

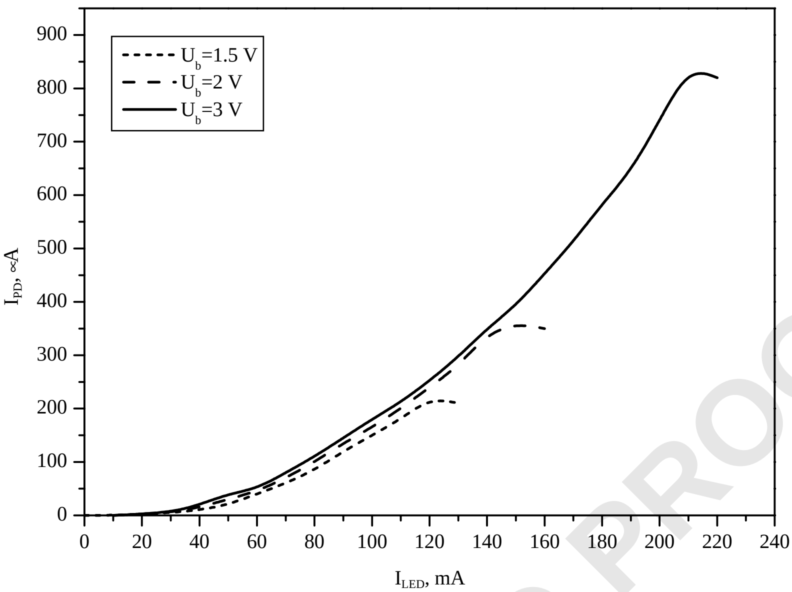

Fig. 2. PD current versus LED current in the porous silicon-based optoelectronic unit with 7 μm alumina waveguide between LED and PD.

still has perspectives to be further optimized in order to reduce optical losses in the waveguide and to increase the PD efficiency. This work is in progress.

Special attention has been paid to the time response of the LED. The transient electroluminescence wave form with the minimized time response is shown in Fig. 3. This curve corresponds to the lowest series resistance and capacitance in the LED. The basic feature of the transient electroluminescence can be characterized by the delay time (time delay between the moment when the drive pulse is applied and the moment when light response becomes visible) and the rise time. The delay time of 1.2 ns and the rise time of 1.5 ns can be extracted from the curve presented in Fig. 3 for the voltage pulse of 12 V.

The shortest time response is observed for the maximum bias applied, as it was also described in Ref. [6] for forward biased porous silicon LEDs. However, our electroluminescence devices are faster in comparison with the forward biased porous silicon LEDs, because in our case there is no an injection capacitance, which limits the time response of the light emission. During the light emission from reverse biased junctions the main mechanism of the minor carrier generation is impact ionization at avalanche breakdown. High electric fields are necessary for that. The regular columnar structure of porous silicon promotes the avalanche breakdown due to nonuniform electric field distribution inside the porous layer [7]. The effect of impact ionization at avalanche breakdown is very fast. For example, the time of the avalanche response is estimated to be about 10 ps [8]. The faster carrier generation mechanism explains the shorter time response of our devices in comparison with forward biased porous silicon LEDs.

Thus, we have shown that the developed LED can operate in the nanosecond range. It should be noted that it is not a limit for these devices. By further technology optimization we hope to reach the subnanosecond range, that is promising for LED applications in optical intra-chip interconnects.

4. Conclusion

The analysis of reverse biased PS LED developments for the last 10 years has shown the considerable parameter improvement towards practical implementations of these devices in optoelectronics. The only unresolved problem is insufficient LED efficiency.

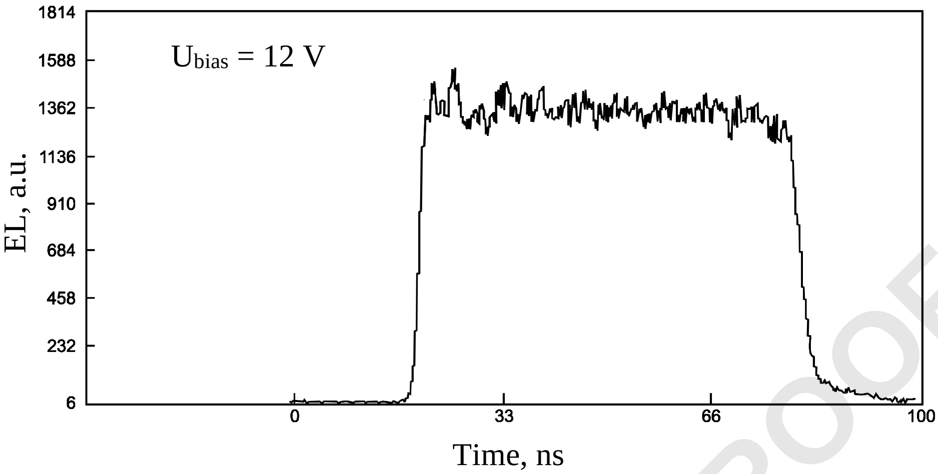

Fig. 3. Electroluminescence time response of the porous silicon LED operating in the avalanche breakdown regime.

Nevertheless, the achieved efficiency level of about 1% allows us to consider some special applications. In particular, reverse biased LEDs could be used for optical intra-chip interconnects. The fabricated prototype of optoelectronic unit based on these LEDs has demonstrated the possibility of using photons for communications inside silicon chips.

5. Uncited reference

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