Reprinted from

Applied Physics Letters

Volume 68 | 8 April 1996 | Number 15

Stable electroluminescence from reverse biased *n*-type porous silicon–aluminum Schottky junction device

S. Lazarouk, P. Jaguiro, and S. Katsouba
Bielorussian State University of Informatics and Electronics, P. Brovki 6, 220600 Minsk, Bielorussia

G. Masini, S. La Monica, G. Maiello, and A. Ferrari[a)]
INFM-Unità di Roma, Università di Roma "La Sapienza," Dipartimento di Ingegneria Electtronica, Via Eudossiana 18, 00184 Rome, Italy

(Received 30 October 1995; accepted for publication 16 January 1996)

pp. 2108-2110

a publication of the American Institute of Physics

Due to an error in production, this article was previously published incorrectly; this is the correct version of the article.

Stable electroluminescence from reverse biased *n*-type porous silicon–aluminum Schottky junction device

S. Lazarouk, P. Jaguiro, and S. Katsouba
Bielorussian State University of Informatics and Electronics, P. Brovki 6, 220600 Minsk, Bielorussia

G. Masini, S. La Monica, G. Maiello, and A. Ferrari[a)]
INFM-Unitá di Roma, Università di Roma ''La Sapienza,'' Dipartimento di Ingegneria Electtronica, Via Eudossiana 18, 00184 Rome, Italy

(Received 30 October 1995; accepted for publication 16 January 1996)

We report the realization of a bright and stable electroluminescent Schottky diode based on aluminum-porous silicon junction. White light, visible in normal daylight, is emitted when a reverse bias is applied to the device, promoting the junction breakdown. The device has a fast (100 ns) rise time of the light emission. An excellent stability, tested over more than one month of continuous operation at a high bias level, is achieved by the complete encapsulation of the active porous silicon under a transparent alumina layer. The external power efficiency of light emission is 0.01%. © *1996 American Institute of Physics.* [S0003-6951(96)00112-2]

The possibility to obtain visible light emission from silicon devices has been considered an important target for years. Various approaches have been attempted in the past and recent years.

Room-temperature visible light emission from reverse biased *p-n* crystalline silicon junctions were first reported in 1955,[1,2] and more recently in Ref. 3. The measured quantum efficiency (QE) in both cases did not exceed 10^{-5}%, making those approaches impractical for device applications.

Porous silicon has been demonstrated to be a promising material for visible light emission. Many solid state devices with different structures have been presented: light emission was observed from Au/PS/Si structures[4] showing a QE of 0.01%; from p^+-n-n^+ PS homojunctions[5] revealing a 0.2% QE under pulsed operation; or from an ITO/*p*-PS/*n*-Si structure,[6] that reached a QE greater than 0.1% in continuous operation. All devices showed degradation phenomena during operation.

In this work, we report a device showing broadband and extremely stable emission, and quite high power efficiency (PE=0.01%). PE is an important figure of merit for applications. This device is based on Schottky junctions between aluminum and *n*-type PS, working in the breakdown region.

The initial substrate was a 0.01 Ω cm *n*-type silicon wafer. The porous silicon layer formation was performed in a transition regime[7] in 1% HF aqueous solution, with 4 mA/cm^2 current density for 5 min, obtaining about a 1 μm thick PS layer. A 100 W tungsten light source at 10 cm from the sample was used during the anodization process.

The Schottky junction was formed by 1 μm magnetron sputtering aluminum deposition over the porous layer, soon after a cleaning bath into 1% HF solution. The device pattern was defined by electrochemical anodization of the surrounding aluminum.[8] The silicon wafer was finally diced and single devices encapsulated into standard packages. In Fig. 1 a scheme of the device structure is sketched; in the inset a microscope view of the operating device is reported, showing the yellowish-white emission at the border of the aluminum pad.

Figure 2 shows on a double log scale the current–voltage characteristics of the device (circles), obtained using a Keithley 236 source measure unit. In the same figure different fit curves are reported. Curve (a) is obtained by a simple Schottky diode model, curve (b) is obtained using the SPICE simulation program and adding to the model a series resistance, a parallel resistance, and a 2.5 V breakdown voltage.

Reverse characteristics in the breakdown region, where electroluminescence starts, are not fitted by these simple models. A good agreement between model prediction and experimental data can be obtained assuming a model com-

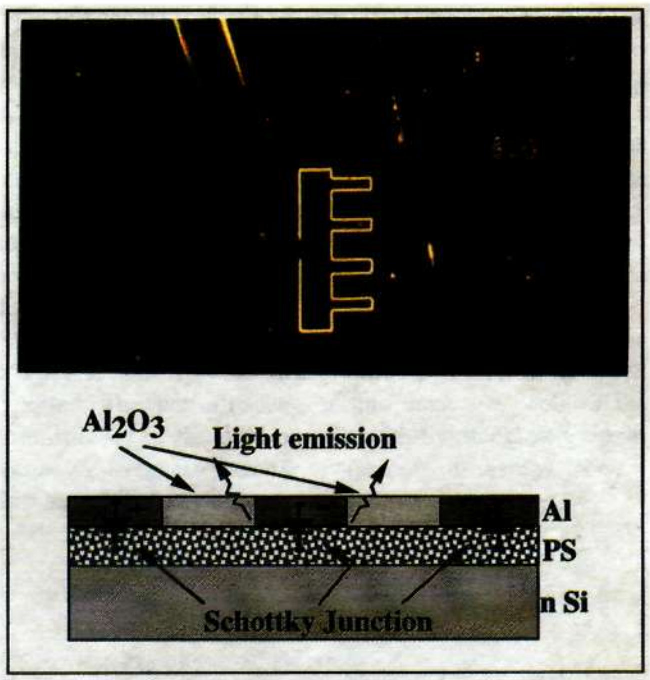

FIG. 1. Scheme of the presented device. The inset shows a microphotograph evidencing the light emission from Al pad perimeter.

a)Electronic mail: ferrari@diewshp1.ing.uniroma1.it

 0003-6951/96/68(15)/2108/3/$10.00

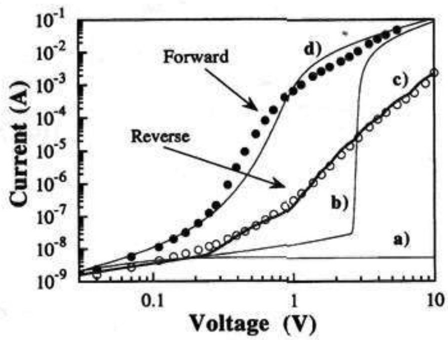

FIG. 2. Current/voltage characteristics of the device. The experimental data are represented by circles. Continuous lines correspond to: (a) Schottky diode model; (b) the same model completed with series and parallel resistance and 2.5 V breakdown voltage; (c) model composed of a set of diodes with different breakdown voltages and connected in parallel. Curve (d) represents the forward simulated characteristic for all the three models.

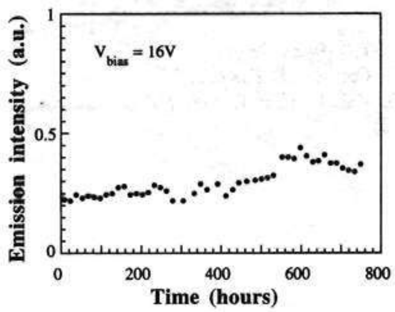

FIG. 4. Intensity of light emission vs operating time.

posed of a set of diodes with different breakdown voltages, connected in parallel [curve (c)]. This approach is suggested by the columnar structure of the n-type porous layer.[7,9] In fact, we suggest that different needles, in the frame of the porous structure, act as independent diodes which enter the breakdown region at different values of the applied voltage due to their different length and size.

Very similar forward characteristics [curve (d)] are obtained using the three models. The forward characteristics allows the extraction of the junction quality factor (n=2.9) and saturation current density ($J_0 \approx 1.6\times 10^{-5}$ A/cm^2). Indeed the low value of the ideality factor accounts for the good quality of the junction.

The electroluminescence (EL) emission of our device is broad, covering the whole visible range and resulting in a yellowish-white light to the eye.[10] This kind of emission is typical of light emitting devices based on junction breakdown processes[2,3] and can be originated by the intra- or interband transitions of hot carriers generated in the avalanche process.

When EL starts, at about 6 V, light can be observed by a microscope as separate spots, the so-called microplasmas as in Ref. 2. The number of visible spots increases while increasing the applied voltage. At 10 V of applied voltage a continuous emitting line is visible, at the edge of the aluminum contact (inset in Fig. 1). This effect agrees with the

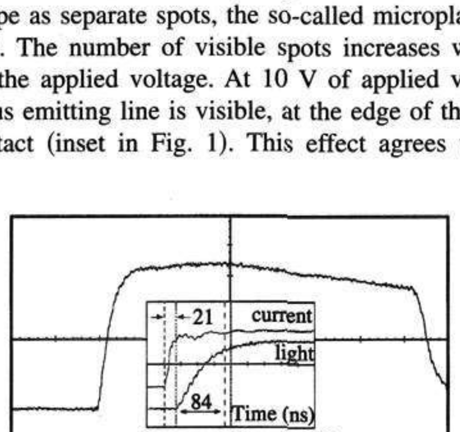

FIG. 3. Time response of device light emission under a 500 mA amplitude current pulse. In the inset the light emission rise time is evidence and compared with the driving current pulse to show the response delay time.

preceding discussed model, suggesting a structure of different parallel diodes with different breakdown voltages.

It should be noted that PL and EL spectra are quite different. The PL spectrum from the porous layer is peaked at 650 nm and has a FWHM of about 150 nm.[10]

Device speed has been measured detecting the light emitted under a pulsed driving current. A fast photodiode connected to a digital oscilloscope has been used for this purpose. The result is shown in Fig. 3: the rise time of the light pulse is about 80 ns; a delay time of around 20 ns between the application of the driving pulse and the start of the light response is visible. The origin of this delay is still under study.

External PE has been evaluated comparing the power detected by a pyrometer and the driving electrical power. A 0.01% PE is obtained at a 100 mA level of driving current. It must be underlined here that due to the opacity of the aluminum pad, only the light generated at the perimeter of the pad can escape from the device and reach the detector. This small fraction of the emitted light can be estimated, from geometrical considerations, to be a few percent of the total generated light and can be increased by making more interdigitated the shape of the aluminum pad. Based on this estimation a reasonable 0.1% external PE could be achieved by simply optimizing the mask used for lithography.

Device stability has been tested over more than one month of continuous operation. In Fig. 4, the intensity of the light emitted as a function of the time is reported: far from showing any degradation, the device seems to slightly improve its performances. The voltages applied to the device during the stability test was 16 V.

In conclusion, the fabrication and characterization of a bright and stable porous silicon based light source has been reported. The performances of this device as well as the compatibility of the used process with the integrated circuit technology suggest possible applications in display fabrication and optoelectronics.

[1] R. Newman, Phys. Rev. **100**, 700 (1955).

[2] A. G. Chynoweth and K. G. McKay, Phys. Rev. **102**, 369 (1956).

[3] J. Kramer, P. Seitz, E. F. Steigmer, H. Auderset, B. Delley, and H. Baltes, Sens. Actuators A **37-38**, 527 (1993).

[4] P. Steiner, F. Kozlowski, and W. Lang, Appl. Phys. Lett. **62**, 2700 (1993).

[5] J. Linros and N. Lalic, Appl. Phys. Lett. **66**, 3048 (1995).
[6] A. Loni, A. J. Simmons, T. I. Cox, P. D. J. Calcott, and L. T. Canham, Electron. Lett. **31**, 1288 (1995).
[7] M. Bertolotti, F. Carassiti, E. Fazio, A. Ferrari, S. La Monica, S. Lazarouk, G. Liakhou, G. Maiello, E. Proverbio, and L. Schirone, Thin Solid Films **255**, 152 (1995).
[8] S. Lazarouk, I. Baranov, G. Maiello, E. Proverbio, G. de Cesare, and A. Ferrari, J. Electrochem. Soc. **141**, 2566 (1994).
[9] M. Binder, T. Edelmann, T. H. Metzger, G. Mauckner, G. Goerig, and J. Peisl, E-MRS Symposium, Strasbourg, May 22–26, 1995.
[10] S. Lazarouk, V. Bondarenko, P. Pershukevich, S. La Monica, G. Maiello, and A. Ferrari, Mater. Res. Soc. Symp. Proc. **358**, 659 (1995).