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Visible light from aluminum–porous silicon Schottky junctions

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Abstract

The fabrication technologies and the properties of light-emitting devices based on Al–porous silicon (PS) Schottky junctions have been developed. Bright light emission, visible by the naked eye at normal daylight, is observed at the edge of the electrodes under reverse bias.

The electroluminescence (EL) starting voltage is in the range 5–18 V, depending on the doping level of Si substrate. The current level at which the EL starts is around 1 mA for devices of 2.3×10^{-3} cm^2 area. The light emission intensity increases with increasing current density. EL spectra were broad, covering the whole visible range.

The time stability was excellent for all tested devices: the EL intensity did not show remarkable changes, even after more than ten days of continuous light emission at voltages lower than thermal breakdown.

Keywords: Aluminium; Silicon; Schottky barrier; Electrochemistry

1. Introduction

Light-emitting devices on the base of porous silicon (PS) open a wide field of applications for optoelectronics. In the recent years a big progress has been made in the efficiency and reliability of electroluminescent devices based on PS [1,2], nevertheless many efforts have still to be performed, in order to optimize the main features of the fabricated devices.

An improvement in electroluminescence (EL) time stability was achieved by replacing the hydride surface of porous silicon by silicon oxide [3]. In this work the properties of Al/PS Schottky junctions with different doping are reported. As already described in Ref. [4], the used electrochemical process parameters for porous silicon formation result in oxygen passivation of the porous surface. The following aluminum anodization for forming contacts provides a further protective transparent layer which prevents the PS layer from direct air contact. The used technological steps have demonstrated to be fundamental for improving the efficiency and time stability of our devices.

2. Experimental

Monocrystalline n-doped silicon wafers with a resistivity ranging between 0.01 and 0.1 Ω cm were used as substrates in our experiments. The technological process for fabricating light-emitting devices with porous silicon–aluminum Schottky junctions was based on electrochemical anodization of silicon and aluminum, as described elsewhere [4–6]. We underline here that in addition to the described process the oxide formed on the top of the porous layer during anodization in a transition regime [5] was removed by a few seconds

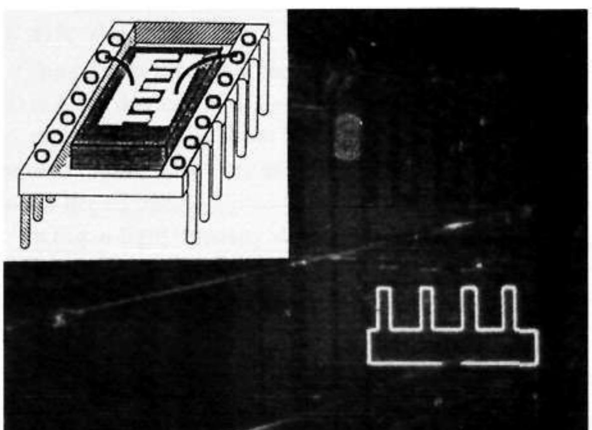

Fig. 1. Photograph by optical microscopy showing an upper view of the developed device. Inset: a schematic view of the encapsulated device.

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Table 1
Substrate resistivities and device characteristics

Substrate resistivity (Ω cm)	Quality factor	Saturation current density (A cm^{-2})	Series resistance (Ω)	Parallel resistance	Breakdown voltage (V)	Built-in voltage (eV)
0.1	1.48	0.34	150	100 kΩ	18	0.47
0.01	2.92	1.6×10^{-5}	80	100 MΩ	2.5	0.73

further treatment in 1% hydrofluoridric aqueous solution just before the aluminum deposition. This step has greatly improved the reliability of the electric contacts.

After processing, wafers were diced and devices were encapsulated into standard packages. Contacts to the external pins were made by microwelded aluminum wires (see Fig. 1).

The electrical characterization of the devices was performed by current–voltage (*I–V*) measurements using a computer-interfaced Keithley 236 apparatus. After porous silicon anodization PL spectra were measured under UV laser excitation at 337 nm wavelength. EL spectra were measured interposing interferential filters (50 nm bandwidth) between the device and a silicon photodiode. Stability tests of the emitted intensity were performed biasing the device with a 114 Hz squared waveform with different current levels. In both cases light intensity was detected by means of a lock-in amplifier. A computer was used to collect data.

3. Results

In Fig. 1 a photograph of an upper view of the device by optical microscopy is shown. In the section a schematic view of the final encapsulated device is depicted. The interdigitated structure of the aluminum contacts, used for obtaining an higher emitting area, is evidenced.

Fig. 2 shows forward and reverse current–voltage characteristics (*I–V*), for light-emitting devices based on different doped silicon wafers. The logarithmic plots allowed a more detailed analysis over three decades of applied voltages. These curves were obtained connecting one pad on the upper surface, and an ohmic contact obtained out of the anodized area.

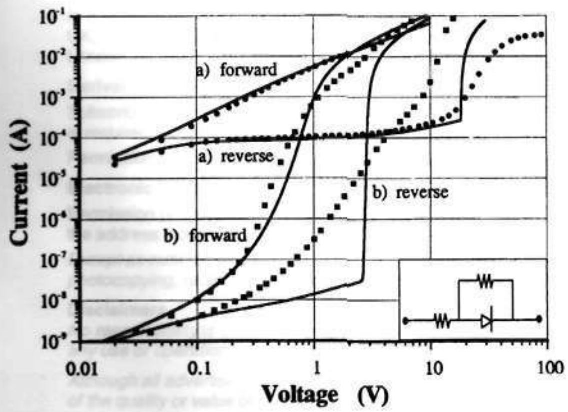

Fig. 2. Forward and reverse *I–V* characteristics, for light-emitting devices formed on (a) 0.1 Ω cm and (b) 0.01 Ω cm doped silicon substrates. The pad area was 2.3×10^{-4} cm^2. Symbols correspond to experimental data, continuous lines are fits obtained from the model shown in the inset.

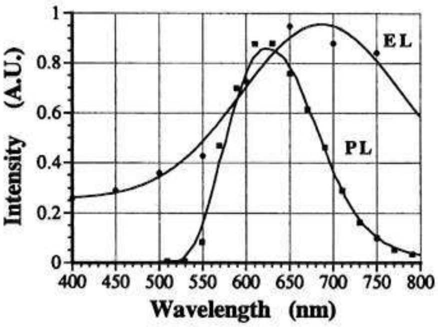

Fig. 3. EL spectrum of the developed device and PL spectrum of the PS layer.

The curve fits corresponding to an electrical model comprehensive of a diode with series and parallel resistance are also reported in Fig. 2. The diode ideality factor (η) ranges between 1.5 and 3 (Table 1). These η values allow to use the classic Schottky theory for our devices.

The EL spectrum for the device with 0.01 Ω cm of initial wafer doping is shown in Fig. 3 together with the PL spectrum of the PS layer. EL spectra were broad, covering the whole visible range; light was observed under a viewing angle of more than 80°. It is important to mention that the light emission was visible in a broad range of temperatures, from -70 °C to 150 °C.

The current level at which the EL starts is in the range 1–10 mA for devices of 2.3×10^{-3} cm^2 area; this corresponds to an applied bias of about 5 V for the sample formed on the base of higher doped initial substrate, and about 18 V for the lower doped one.

In Fig. 4 light intensity versus time curves are reported for different driving currents, showing an high degree of stability, even after many days of continuous operation, at high current levels.

The power consumption under a continuous driving current, for obtaining stable and bright EL under normal daylight, is in the 1–2 W range for samples of 2.3×10^{-3} cm^2 area; anyway, using a pulsed driving waveform with a low duty cycle the emission under daylight was still visible with a power consumption reduced of more than one order of magnitude.

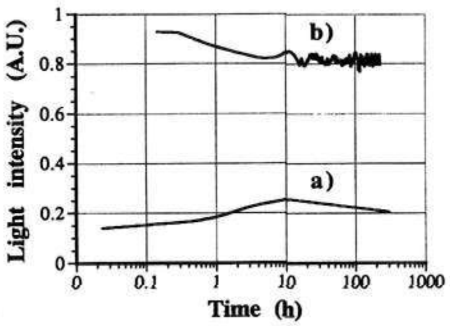

Fig. 4. Light intensity as a function of time at different current levels: (a) 65 mA; (b) 350 mA.

4. Discussion

As shown in Fig. 2, the experimental *I–V* curves were well fitted by the simple diode model except for the breakdown region. The measured current increase in that region is slower than the one predicted from the usual breakdown models [7], as it is visible from the simulation. The modeling of the breakdown, fundamental for understanding the light-emitting mechanism appearing in this region, is currently under study. Promising results seems to come directly from the suggested physical model [5] of porous silicon obtained in the transition regime. The proposed model consists of silicon needles surrounded by a skeleton of silicon oxide which add mechanical stability to silicon crystallites. The presence of silicon oxide was confirmed by FTIR measurements. In this picture every needle could behave as a single diode connected to the aluminum top layer. Preliminary results concerning many parallel diodes with a gaussian distribution of dimensions are encouraging [8].

Measured electroluminescence spectra confirm [4] the different origin of the EL and PL phenomena: while PL spectrum shows typical emission of porous silicon, EL is broader and shows red shift of peak position with respect to PL. The resulting light covers the entire visible range and appears yellowish–white to the eye. As we proposed in [4] the origin of the EL should be found in the recombination of hot carriers in the high field region of the junction.

Time stability of our devices is excellent, compared with similar class devices [1,3], both at high and low bias levels as reported in Fig. 4: after more than 10–15 days of continuous operation no appreciable degradation of the light emission intensity was recorded. Passivation of active porous silicon surface by the aluminum metallization built-in transparent alumina has demonstrated to be the key step to obtain such stability performances.

5. Conclusions

In this work the properties of electroluminescent devices on the base of Schottky junctions between aluminum and porous silicon formed on different doped substrates are reported. The obtained main features are: small operation voltage, broad emission spectra, high brightness, and a very high time stability. The developed devices are promising for applications in light-emitting matrix panels.

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