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Abstract

The electrical behaviour of electroluminescent Schottky diodes fabricated on the base of aluminum and n-type porous silicon is reported. Porous silicon was formed by electrochemical etching in HF aqueous solutions of n-type monocrystalline silicon and of degenerate n^+-type polysilicon. The polysilicon layer was formed on monocrystalline silicon substrate by low pressure chemical vapour deposition (LPCVD). The electroluminescence (EL) starting voltage was in the range 4–20 Volt, depending on the doping level of Si substrate; polysilicon samples showed a higher starting voltage. Developed devices showed broad EL spectra, covering the whole visible range. Electrical measurements include current–voltage characteristics and capacitance–voltage characteristics. Time response and stability of the light emitting devices was also measured, showing excellent speed and reliability characteristics.

1. Introduction

Visible electroluminescence (EL) from devices based on porous silicon (PS) opens a wide variety of possible applications from the technological point of view. In the recent years many solid state devices with different structures were presented: light emission was observed from Au/PS/Si structures [1,2], from p–n heterojunctions [3] or from heavily doped p^+–n^+ PS homojunctions [4] at low forward bias voltage. Nevertheless, for practical use important problems to be overcome are the efficiency and stability of light generation.

We already reported [5–7] the technological process for obtaining bright and extremely stable EL from reverse biased Schottky junctions between aluminium and n-type PS. In this work electrical properties for EL devices based on different doped n-type crystalline silicon and polysilicon is reported.

The fabrication technology of the obtained structures is compatible with modern silicon integrated circuits. The reported operating characteristics of the devices open the way for many applications, including the optical communications field.

2. Experimental

Devices were fabricated using monocrystalline n-type silicon wafers with a resistivity of 0.01, 0.1 Ω

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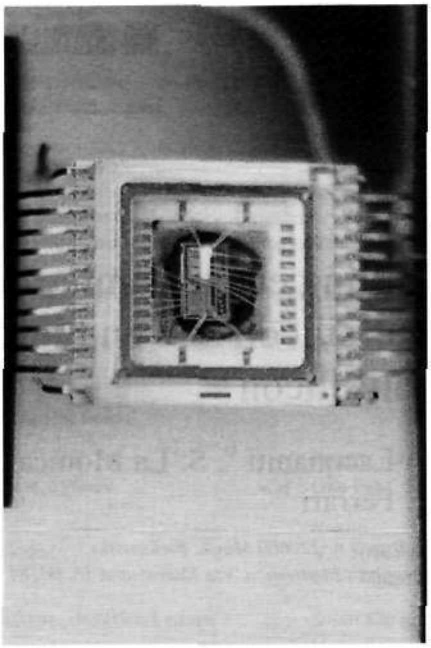

Fig. 1. The incapsulated light emitting device.

cm (CS1 and CS2 respectively in the following) [8] and low pressure chemical vapour deposition (LPCVD) polysilicon deposited onto 4.5 Ω cm n-type silicon wafers (P1). A 1 μm thick polysilicon layer was phosphorous doped, resulting in a resistivity of 10^{-3} Ω cm [7]. The PS layer was formed by anodization in transition regime, in 1% HF aqueous solution at a current density of 2–5 mA/cm^2 [6,9]. During anodization the samples were illuminated by a tungsten lamp from the front side.

A 0.5 μm thick aluminum layer was deposited by magnetron sputtering onto the porous layer. The Al electrodes (pads, area = 10^{-4} cm^2) were obtained by standard photolithography and a subsequent electrochemical anodization process on aluminum, as described in Ref. [10]. Light emission was visible through the transparent insulating alumina (Al_2O_3) areas around the aluminum pads, then wafers were diced and devices were encapsulated into standard packages, as shown in Fig. 1. Contacts to the external pins were established by microwelded aluminum wires.

The electrical properties of the devices were measured by current/voltage (I/V) measurements using a computer-interfaced apparatus (Keithley 236), while a impedance analyzer (HP 4192A) was used for capacitance/voltage (C/V) measurements.

The time response was measured driving the device with a current pulse 1 μs long, with a 20 ns rise time. The current amplitude was 500 mA. The emitted light was collected by a photodiode and the time response was recorded with digital oscilloscope.

3. Results

Fig. 2(a) shows the experimental current/voltage characteristics for different doped crystalline silicon and polysilicon, obtained connecting one aluminum pad and an ohmic contact on the upper surface out of the anodized area. EL appeared at the edge of a pad when the PS/Al junction was reverse biased (i.e. negative on aluminum). The EL starting voltage decreased with increasing of doping level of Si substrate. The onset value ranged from 4 to 20 V. Polysilicon samples showed a higher starting voltage. The intensity of the emitted light increased with applied voltage for all the samples; the highest brightness was achieved with the device based on 0.01 Ω cm monocrystalline silicon substrate (CS1). Developed devices showed broad EL spectra, covering the whole visible range.

The forward characteristics of all devices are well fitted even by a simple model consisting of a Schot-

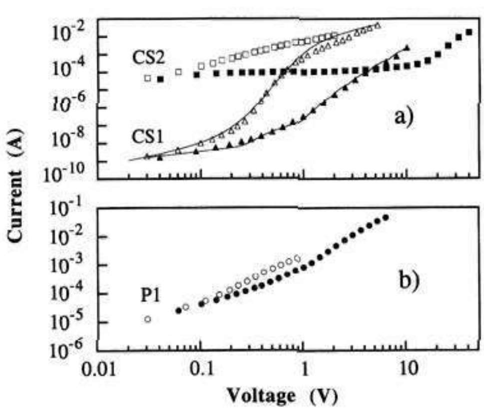

Fig. 2. Current voltage (I/V) curves for devices based on crystalline (a) and poly (b) materials. Forward currents are reported with empty symbols, reverse characteristics with filled symbols. In (a) symbols represent experimental data while solid lines are fits obtained with the model outlined in the text.

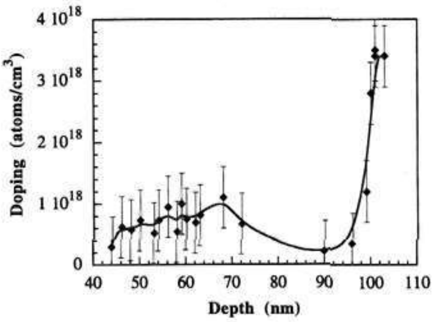

Fig. 3. Doping profile obtained by capacitance–voltage measurements on device CS1: the presence of a shallow layer depleted from doping atoms is evident. The solid line is a guide to the eye.

tky diode with a series resistance (Fig. 2(a)); evaluated ideality factors range from 1.5 to 3 for crystalline based devices and from 4 to 10 for polysilicon devices. On the other hand the current increase in reverse bias during breakdown is less steep with respect to usual models [11]. Satisfactory agreement with the experimental data was achieved using a model consisting of many diodes with different breakdown voltages connected in parallel, as reported in Fig. 2(a) for the CS1 sample.

The doping profile in the porous layer was determined by reverse bias capacitance/voltage (C/V) technique [12], p. 100. The results for CS1 are shown in Fig. 3, from which the presence of a thin surface layer depleted from doping atoms is evident [13]. Similar depletion layers resulted also from measurements performed on the other samples.

The time response of the light emission, due to a current pulse of 500 mA amplitude is shown in Fig. 4. The 10–90% rise time was measured in 80 ± 15 ns. A delay of 20 ± 5 ns between the rise of the

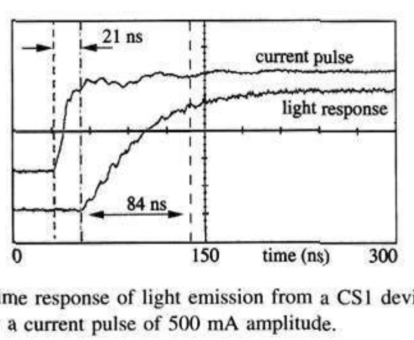

Fig. 4. Time response of light emission from a CS1 device when driven by a current pulse of 500 mA amplitude.

driving pulse and the start of the light signal was observed.

4. Discussion

The proposed model is suggested by the peculiar structure of the porous layer. The presence of cylindrical shaped structures with the axis perpendicular to the surface has been reported [14] for PS layers; a structural model was proposed in Ref. [6], consisting of a structure with silicon wires surrounded by a skeleton of passivating silicon oxide. For this reason different wires can be considered electrically isolated one each other, behaving as independent diodes. Each diode in this model is associated to a set including all the wires with a certain section value. Different dimensions affect curvature radius of the contact with the upper aluminum layer, resulting in a distribution of the breakdown volgates [12], p. 83. The used model consisting of parallel diodes fits very well the entire current voltage properties including the breakdown region (Fig. 2(a)), where the EL phenomenon occurs.

The C/V measurements (Fig. 3) show a thin surface region depleted from doping atoms in the porous layer. The applied reverse bias mainly drops in this shallow region, resulting in a high value of the electric field which promotes breakdown. Recombination of hot carriers generated by this process can be the origin of the EL phenomenon in our devices, having a porous silicon layer as an active luminescent layer with modified bandgap properties. The ideality factor ranges from 1.5 to 10 and can be explained by a density of surface states appearing at the interface between silicon wires and passivating silicon oxide layers. These surface states can change the luminescent properties of porous silicon. This change is supported by the recorded broad spectra of the emitted light, covering the whole visible range [9]. This broad emission could not be generated deep in the bulk, due to the high values of silicon absorption coefficient for low wavelengths of the visible range [15].

The stability of the emitted light was excellent: after 15 days of continuous emission under squared waveform driving current no appreciable degradation of the intensity was observed.

5. Conclusions

In this work the properties of EL devices on the base of Schottky junctions between aluminum and porous silicon formed on different substrates are reported.

The fabricated devices showed a small operation voltage, a fast time response, broad emission spectra and a high time stability. These excellent features open the way for applications in light emitting display devices. Moreover, polysilicon based devices, even showing weaker brightness under the same driving conditions as compared to the crystalline based devices, are promising for low-cost and large area flat panel color displays.

Finally the high measured speed of the presented devices suggest applications also in the field of silicon based optoelectronics [16].

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