ELECTROLUMINESCENCE IN POROUS SILICON FILMS OF REVERSE BIASED SCHOTTKY JUNCTIONS

P. Jaguiro
JV "Belaya Vezha", Minsk, Belarus
S. Lazarouk., A.Smirnov
Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus
L. Pavesi
Trento University, Trento, Italy

Abstract

The peculiarities of electroluminescence in porous silicon films of reverse biased Schottky junctions are shown. The electroluminescence mechanism is discussed. The parameters of reverse biased porous silicon light emitting diodes are presented. Applications of a microdisplay based on this devices integrated with drivers on Si-chip are analyzed.

Introduction

We are observing the hasty growth of silicon microelectronics, chips are becoming larger and are working faster. So the problem of fast data transfer on the chip and outside becomes the main one. The standard solution is communication by optoelectronics, but silicon is not the best optoelectronic material.

The new period in investigation of silicon optical properties is beginning after discovering the bright visible photoluminescence on PS. These investigations elevate hopes to improve zone structure of silicon and create effective Si-based visible LED. But trying to change the zone structure is not the unique possibility for silicon-based optoelectronics.

Another way to produce visible light is heating. Of course, it is nonsense to heat silicon, but it is possible to heat only electron (hole) gas in it. This method is widely used for different semiconductors [1]. For this method it is needed to originate a region with high electric field, under the field electrons are accelerating and achieving certain effective temperature. So masses of an electron and a silicon atom are differ greatly, as energy dissipation by collisions is low. So the effective electron gas temperature can achieve few thousands degrees in silicon at room temperature. The emissive spectrum is continuos and corresponds to effective electron gas temperature. The highest electric field is usually present in avalanche structures, so this LED are extremely fast [2].

Constructions, electrical and electroluminescence behavior of the avalanche LED

Even in 1950-th it was found that reverse biased p-n junctions can emit visible light with initial quantum efficiency up to 10^{-8} [3]. Light emission usually is not uniform and consists from small dots. It is very difficult to make measurements under such conditions, so all experimenters tried to achieve a homogeneous light emission. By using perfect silicon crystal and special technologies uniform brightness was achieved, but power efficiency is extremely low [4].

Electroluminescent structures based on PS have been investigated too [5]. Note that the PS diodes sometimes demonstrated electroluminescence under both reverse and forward bias. Sometimes under forward bias a voltage drop on PS structure is enough to achieve avalanche in patchy centers.

In this paper we are considering LED based on Shottky junction PS - Al at reverse biased [6]. Silicon substrates (n-type 0.1 or 0.01 Ohm cm) are used, anodization process is carried out in transition regime (between standard and electropolishing ones). Anodization deep is 1 micron for standard [6] and 0.5 micron for the new samples. Aluminum layer is deposited on PS by magnetron sputtering. Then aluminum contact pad (typical size is ~0.5*0.5 mm) and protective aluminum oxide cover are formed under special electrochemical process. This process is technologically easy and provides excellent purification and protection for the PS layer. The samples demonstrate good reproducibility and excellent stability even at high current densities. This is enough for science investigations, but the main disadvantage for practical use is shielding of the light by the aluminum pad. Light emission exists only from thin line (1 micron or less) around the aluminum pad, and total light losses are very high. Relation "light emission area/total contact area" is only ~ 1/50, besides at least 80% of light is loosed due refraction in PS. Main parameters of these LEDs are collected in the table.

Next light emission devices, based on monocrystal silicon (n-type 4.5 Ohm cm) were made and investigated [8]:

- reverse biased LED, with electrode from annealed silver dust
- reverse biased LED, with electrode from magnetron sputtered Al after special anodization process. This is long time anodization with forwarding the process under photoresist mask, so the lot number of crystallites is not completely transformed into oxide. Note that detectable light emission was not achieved for diode, based on monocrystal silicon with electrode from magnetron sputtered Al after standard anodization process.

Parameters of monocrystal and PS LEDs were compared by measuring in the same conditions. Light emission was measured by photo multiplier, with sensitivity region from 330 to 700 nm and maximum at 500 nm. So, these measurements can be interpreted as rough evaluation of visible light emission efficiency. Results of the measuring are presented in fig. 1.

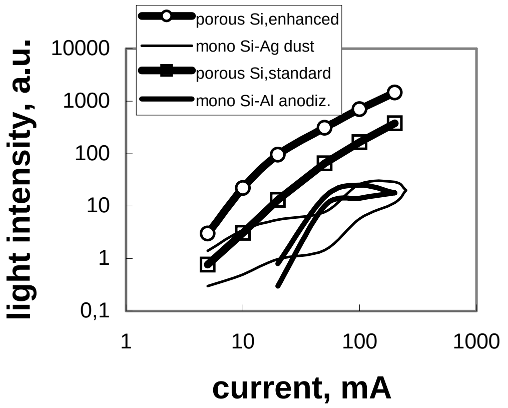


Fig.1. Experimental measurements of different reverse-biased light emission diodes

Light emission from monocrystal silicon is compatible, but significantly low than from PS. Light from monocrystal silicon is not stable - at high current densities the degradation process takes place. This effect exists even in aluminum-silicon diode, where aluminum or aluminum oxide film covers junction surface. Probably, the effect can be explained by low number of light emissive centers on monocrystal Si and damaging certain part of them due to extremely high current concentration.

Electrophysical properties and physical model of the porous silicon layers

Such significant semiconductor properties as effective doping level and dielectric constant are changed in PS. These properties determine

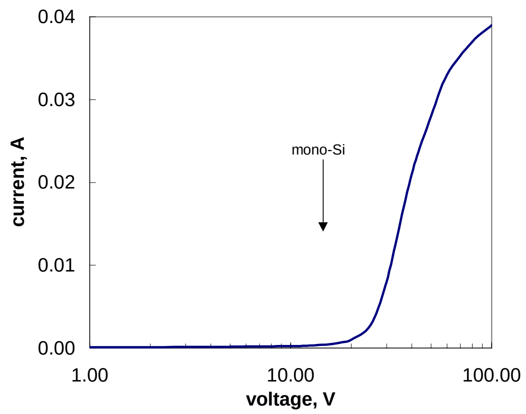
operated temperature	-190…+100 ºC
current density (continuos operation)	200 A/cm^2
current density (pulse operation)	8000 A/cm^2
stability under continuos operation	>2000 hours
external power efficiency (visible & infrared)	10^{-2} %
internal power efficiency (visible & infrared)	1 % estimated
brightness (continuos operation)	10 W/cm^2
brightness (pulse operation)	200 W/cm^2
time response	20 nc

electric field distribution and avalanche conditions and are the most essential for light emission of hot carriers.

The key for electrophysical properties of PS lays in breakdown volt-ampere curves. Note, that more correct is analyzing of low doped structures, because in them tunneling current is negligible.

Breakdown volt-ampere curves for Shottky junction aluminium - PS on 0.1 Ohm·cm n-type silicon substrate [9] are presented in figure 2.

Fig.2. Breakdown volt-ampere curves



The shape for PS cannot be described as usual breakdown curve. Of course it is possible to explain such shape as a result of composing of a set of diodes with different breakdown voltage, connected in parallel [6]. The distribution of the breakdown voltages is explained by different curvature radius of avalanche centers. But why breakdown voltage for PS is higher than for monocrystal one? Lower breakdown voltage for monocrystal silicon produces a certain technological problem. So in our devices we use the continuous PS layer to prevent avalanche in contact with monocrystal silicon.

The structural model for PS, proposed in [10] and presented in fig.3 A, suggests that PS consisting of silicon wires surrounded by a skeleton of silicon oxide. Different wires are electrically isolated and are behaving as independent diodes.

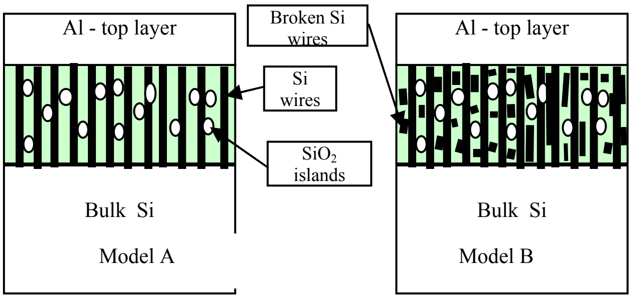


Fig.3. Different models of porous silicon

Considering such structure as macro semiconductor material, the space charge density is decreased proportionally to PS density. It corresponds to lower effective doping level, so breakdown voltage must be higher. But in porous materials the polarization ability and correspondent dielectric constant decreases too, so electric field at the same charge density is higher, and breakdown voltage must be lower. It is easy to calculate the result: let relative PS density be $\boldsymbol{D}$, dielectric constant of monocrystal silicon be ε_{Si} , than effective dielectric constant ε_D is

$$\varepsilon_D = (\varepsilon_{Si}-1)*\boldsymbol{D} + 1 \qquad (1)$$

If space charge density for monocrystal silicon is $\boldsymbol{N}$, than for PS we have the thickness of depletion layer at applied voltage $\boldsymbol{V}$

$$W_D \sim \mathrm{SQRT}(V\varepsilon_D/N*D) \qquad (2)$$

So it is possible to find the effective N_{eff} for monocrystal silicon, at which the thickness of depletion layer is the same as in the PS at the same applied voltage:

$$N_{eff} = N*D*\varepsilon_{Si}/\varepsilon_D = N*D*\varepsilon_{Si}/\{(\varepsilon_{Si}-1)*D+1\} \quad (3)$$

If we have the same thickness at the same voltage it means that avalanche conditions is the same.

For monocrystal silicon breakdown voltage is approximately proportional to $N^{2/3}$ (in voltage range 8…80 V), so it possible to calculate relative change of the breakdown voltage via D. The results are presented in figure 4. It is easy to see that under this model the PS has low increasing breakdown voltage, which is not enough to explain the experimental data.

To move the model to experimental data we suppose that many of silicon wires in silica skeleton are broken, so they are disconnected and cannot produce spatial charge (figure 3 B). But silicon has high dielectric constant and these wires significantly change electrophysical parameters. Below we consider example with density $\boldsymbol{D}$, but only 1/3 $\boldsymbol{D}$ is perfect wires and 2/3 $\boldsymbol{D}$ is broken wires.

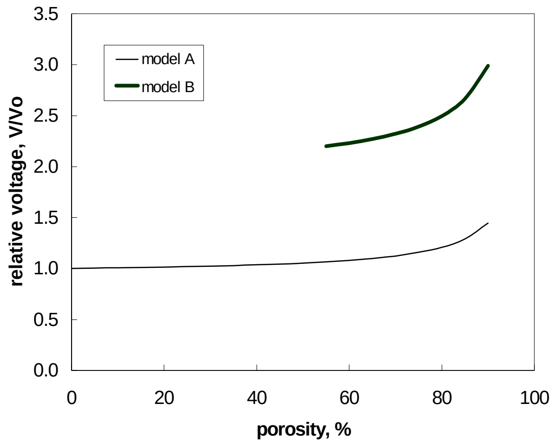
So, ε_D is the same, but

$$N_{\mathrm{eff}} = N_D*\varepsilon_{Si}/\varepsilon_D = 1/3*N*D*\varepsilon_{Si}/\{(\varepsilon_{Si}-1)*D+1\} \quad (4),$$

which corresponds to rather realistic breakdown voltage (see fig.4).

Regret to say that such analysis is not available to the most efficient high doped PS

Fig.4. Relative breakdown voltage via porosity



structures, because of significant tunneling current. But it is important to note, that if we use high doped monocrystal silicon, which has not avalanche breakdown but tunneling one, we can achieve lower effective doping level and avalanche breakdown in porous structure.

Hot carriers light emission in nonplanar structures

Light emission from hot carriers at avalanche breakdown and impact ionization occurs in different semiconductors. The spectrums are wide and practically without structure.

There are theoretical works in which the mechanism of light emission by hot electron is investigated, but in such works dependence of energy distribution from real breakdown conditions is out of frames [11]. Avalanche breakdown in diodes is carefully investigated, but usually results are limited in electric parameters of the devices [12]. So, the theory, which can relate topology and light emitting parameters of avalanche diodes [8], helps to better understanding the behavior of monocrystal and PS LEDs.

The problem of finding the spectrum and efficiency of light emission from avalanche monocrystal silicon LEDs with different topologies was solved “step by step” by finding [8]:

- spatial distribution of electric field under avalanche breakdown conditions;
- dependence of temperature of electron gas from the electric field strength;
- dependence of local emission parameters from the local electron gas temperature;
- total spectrum and efficiency by spatial integrating.

Results for planar and spherical topologies at different doping levels are calculated for the same avalanche current and are presented in figure 5 in arbitrary, but the same units. Blue shift in spectrums and higher efficiency are evidence at more doped and more curved systems. When topology changed from planar to spherical with radius 250 nm, then quantum efficiency improved on 10…30000 times.

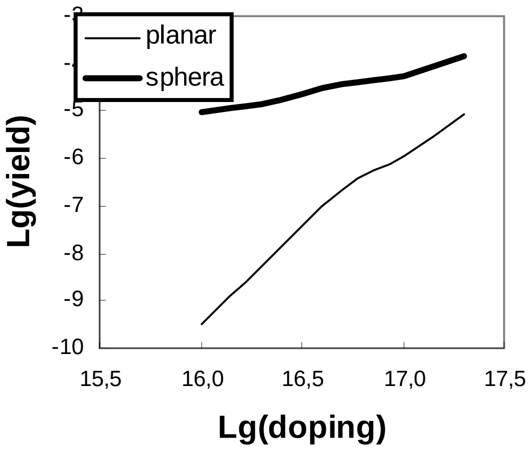


Fig.5. Quantum yield in visible range via doping level for planar and spherical topologies

Conclusions

Avalanche LEDs on monocrystal and PS are compared. Physical model is proposed to explain breakdown behavior of the PS layers. Light emission of hot carriers in nonplanar structures is considered.

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