A Full Inorganic Electroluminescent Microdisplay

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Abstract

Design and fabrication process of a full inorganic electroluminescent microdislay based on aluminum / nanostructured porous silicon reverse biased light emitting Schottky diodes are discussing. Being of a solid state construction, this microdisplay is cost-effective, thin and light in weight due to very simple device architecture. Its benefits include also super high resolution, wide viewing angles, fast response time and wide operating temperature range. The advantages of full integration of a LED-array and driving circuitry onto a Si-chip will be also discussed.

1. Introduction

A new very fast growing segment of electronic industry is the industry dealing with super miniature displays or microdisplays. They are finding the place in portable wireless communication devices, computing tools, digital still cameras, camcorders, advanced sell phones, and toys.

In principle, the simplest type of microdisplay is a light emitting device because it eliminates the need for an external light source and complicated optics, but their low luminance level limits their application to personal viewers. Most of the known light emissive technologies have been implemented as microdisplay technologies [1,2].

In this paper we are discussing an alternative cost-effective approach based on the usage of Al / nanostructured porous silicon (PS) reverse biased light emitting Schottky diodes fabricated onto a silicon chip together with addressing ICs. The main advantages of such an approach are:

1). The usage of a simple and cost-effective standard bipolar semiconductor manufacturing process which provides full integration of addressing ICs with an array of Al / PS light emitting diodes and helps to integrate a lot of functionality into the display's silicon backplane;

2). Very high resolution and nanosecond response time of a PS LED microdisplay;

3). Low cost and simplicity of PS LED microdisplay fabrication, especially, in the case of passive addressing.

2. State of the art

The first reversed biased PS LED was demonstrated by Richter et al. in 1991 [3]. A PS-layer was formed on a n-type silicon substrate following with the deposition of a semitransparent Au-electrode in order to form the Schottky structure. Light emission with the efficiency of 10^{-5}-10^{-6} was observed in the visible range with the peak of 650 nm [4]. The lifetime of such devices varied from 45 min. to 100 h, after which the emission attenuation took place [5].

In 1995, we made a significant improvement in the efficiency and stability [6] through the formation of an oxidized PS layer protected from atmospheric oxygen by the additional passivation. The oxidized PS layer was formed on a low resistivity n-Si substrate by anodozation in the transition regime [7], providing a continuous anodic oxide on the surface. Moreover, the additional passivation layer of a transparent anodic alumina Al_2O_3 was formed on the PS layer by a selective Al-anodization in an oxalic electrolyte during formation of an Al-Schottky electrode. It ensured the stability of continuous PS LED operation during 1000 h without visible degradation effects and increased quantum efficiency (10^{-3}-10^{-4}) [8].

In 1998, V. Kuznetsov et al. [9] improved a PS LED design in order to enhance the device efficiency till $5\text{x}10^{-3}$. In particular, they replaced the opaque electrode with a semitransparent silver electrode.

In 2000, the more efficient reverse biased PS LEDs have been reported by B. Gelloz et al. [10]. The quantum efficiency of about 10^{-2} has been obtained by using oxidized PS. Porous layer was formed on n+-silicon at 0°C. Then, the PS layer without drying was electrochemically oxidized by anodization in an aqueous solution of sulfuric acid. A Schottky barrier was formed by a transparent ITO deposition. The advancement of the anodization process by this way decreased the size of nonconfined silicon nanocrystals in PS. The enchanced quantum efficiency can be explained by the reduction of leakage carrier flow through the nonconfined silicon nanocrystals. Recently, the highest quantum efficiency of about 1.2x10^{-2} has been obtained by pulsed exitation [11]. Pulse LED operation allows one to reach the highest current density through a LED structure, which corresponds to maximum efficiency values.

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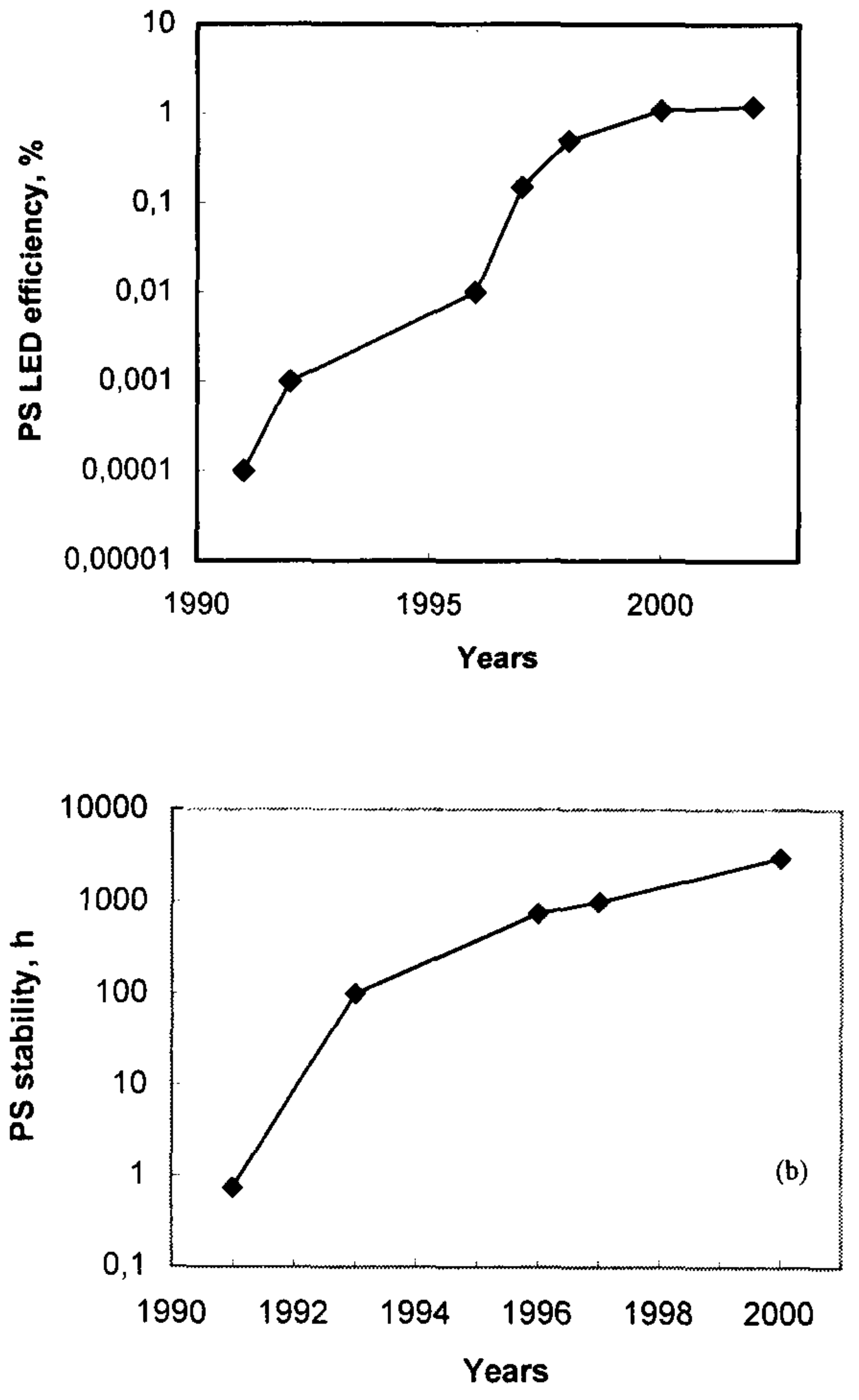

Fig.1. Efficiency (a) and stability (b) improvement of reverse biased PS LEDs.

Some common design ideas are present in all mentioned PS LEDs:

- all are formed on n-type silicon substrates due to the higher Schottky barrier compared to p-type material;
- in addition, n+-silicon substrates are preferable because of minimal series resistance of PS LEDs;
- PS must have homogeneous size distribution of nanocrystals over all the thickness and down to 1 μm. For this reason, oxidized PS was used in the device fabriccation and the temperature of the PS formation was chosen to be 0°C;
- reverse biased LEDs have a nonlinear EL-I characteristics with an efficiency increasing with a current;
- optimized LED geometry and pulsed bias provide maximum LED current with the highest efficiency value;
- reverse biased PS LEDs can be formed also onto polysilicon [12] or amorphous silicon [13] layers as well as onto a transparent sapphire [14] or glass [15] substrates.

3. PS LED array fabrication process

The fabrication process and a PS LED structure are shown in Fig.2. N-type single crystal silicon wafers with the resistivity of 4.5 Om·cm were used as substrates in our experiments. High doped n$^+$-silicon layer of about 100 nm thickness was formed on both sides of wafer by diffusion of phosphorous gas phase at a temperature of 950°C during 40 minutes (Fig. 2a). After doping treatment the surface resistivity of a sample was 10 Om/□ (10^{20} dopant atoms/ cm^3). Then wafers were etched in hydrofluoridric acid in order to remove the oxide formed during thermal treatment [16].

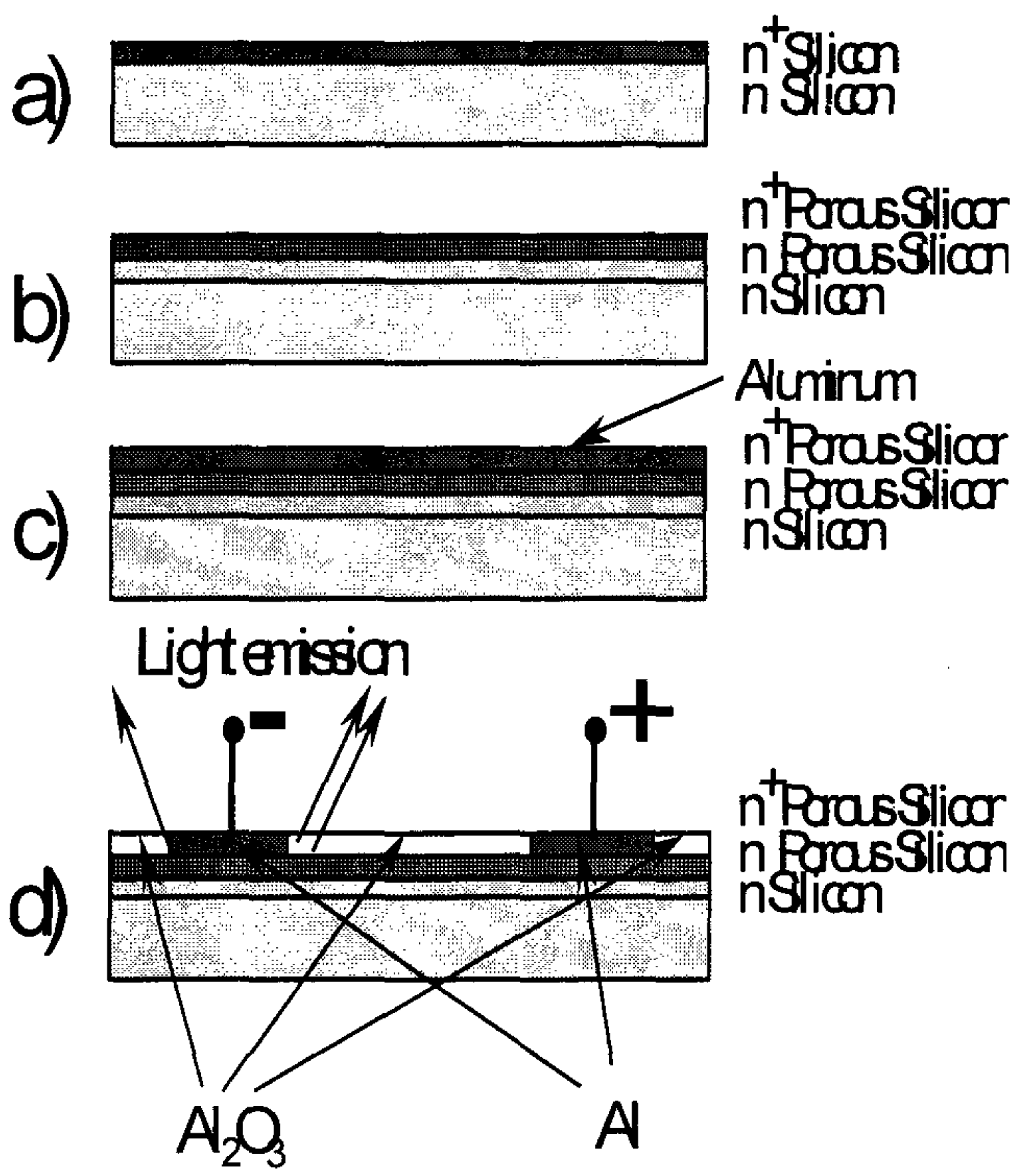

Fig.2. Schematic view of fabrication process and a PS LED structure: a) n-type silicon wafer with n$^+$-diffused layer; b) after anodization in transition regime, PS is formed both in n$^+$- film and in a substrate layer; c)

aluminum layer is deposited by magnetron sputtering; d) the final structure after photolithography and subsequent aluminum anodization. Light emission at the edge of negative biased pad is evidenced.

The PS layer was formed by anodization in transition regime, in 1% HF aqueous solution at 2-5 mA/cm^2. The thickness of PS film was higher than the n$^+$-layer one, so that a thin layer of the n-substrate was also anodized (Fig. 2b).
To obtain metallic contact, 0.5 µm thick aluminum film was deposited by magnetron sputtering onto the porous layer (Fig. 2c). The Al electrodes (pads) were obtained by standard photolitography and subsequent electrochemical aluminum anodization process. Aluminum anodization produced the transparent insulating alumina (Al_2O_3) areas between the aluminum pads so that ligth could be revealed (Fig. 2d).
The electrical contact on the wafer back side (not shown in the picture) was provided by the n$^+$-diffused layer. Devices were biased connecting either two adjacent pads on the upper layer either one of the pads and the back side contact.

4. Experimental results

EL spectra were measured with the computer-aided spectrophotometer PEM-100, equipped with a cooled photomultiplier. PL spectra were measured under UV laser excitation at λ=337 nm.
Visible electroluminescence (EL) was recorded when DC or AC voltages larger than 4V were applied between the aluminium electrodes. The visible EL appears in the dark, at the edge of the electrodes at a reverse bias of 5-6 V. The intensity of emitted light increases with applied voltage. At applied bias higher than 7 V the emitted light was observable by the naked eye at normal daylight. Compared to forward biased solid state porous silicon devices, the structure has an increased stability (after 1000 hours of continuous operation under 7 V reverse bias, no appreciable modification was observed in emission intensity [17].
The dependence of light intensity via current density is shown in Fig. 3.
The EL brightness increases while increasing the applied voltage until thermal breakdown is reached. The thermal breakdown takes place when currents higher than 500 mA are measured through 0.02 mm^2 pad area (the current density referred to the pad area is more than 2500 A/cm^2). Referring to these pad areas, such currents are destructive. Limiting the current in the 200-250 mA range, bright and stable EL is visible even after 1000 hours of light emission. Moreover, current - voltage characteristics are reproducible at different time intervals, even after 1000 h of permanent applied voltage.
It is noticeable that EL intensity is higher when voltage is supplied between two adjacent electrodes than between an Al electrode and silicon substrate. This fact is reasonably related at the possibility to see or not the emission from the maximum electric field region that is under the Al layer when the substrate is the second electrode.

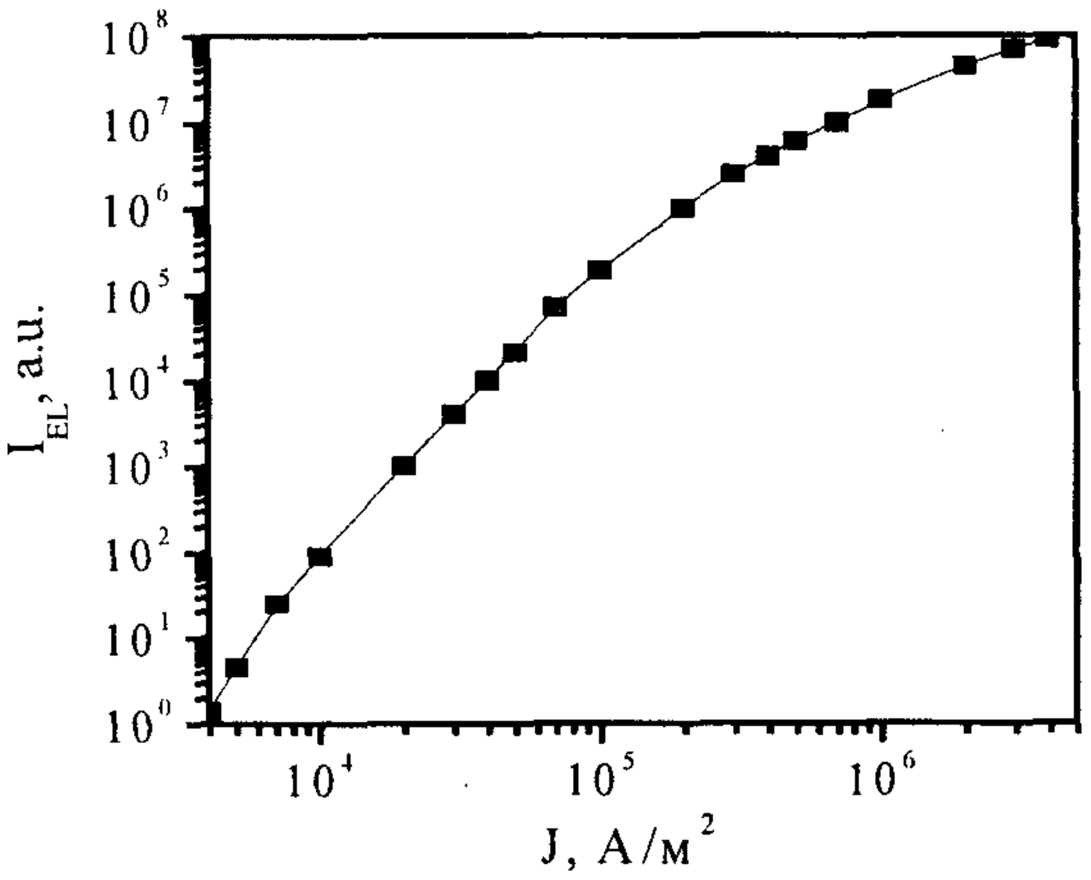

Fig.3. EL light intensity of Al/PS structures via current density.

The EL spectrum, measured in the 1.55 –3.105 eV energy range, for different currents through two adjacent electrodes are shown in Fig. 4.

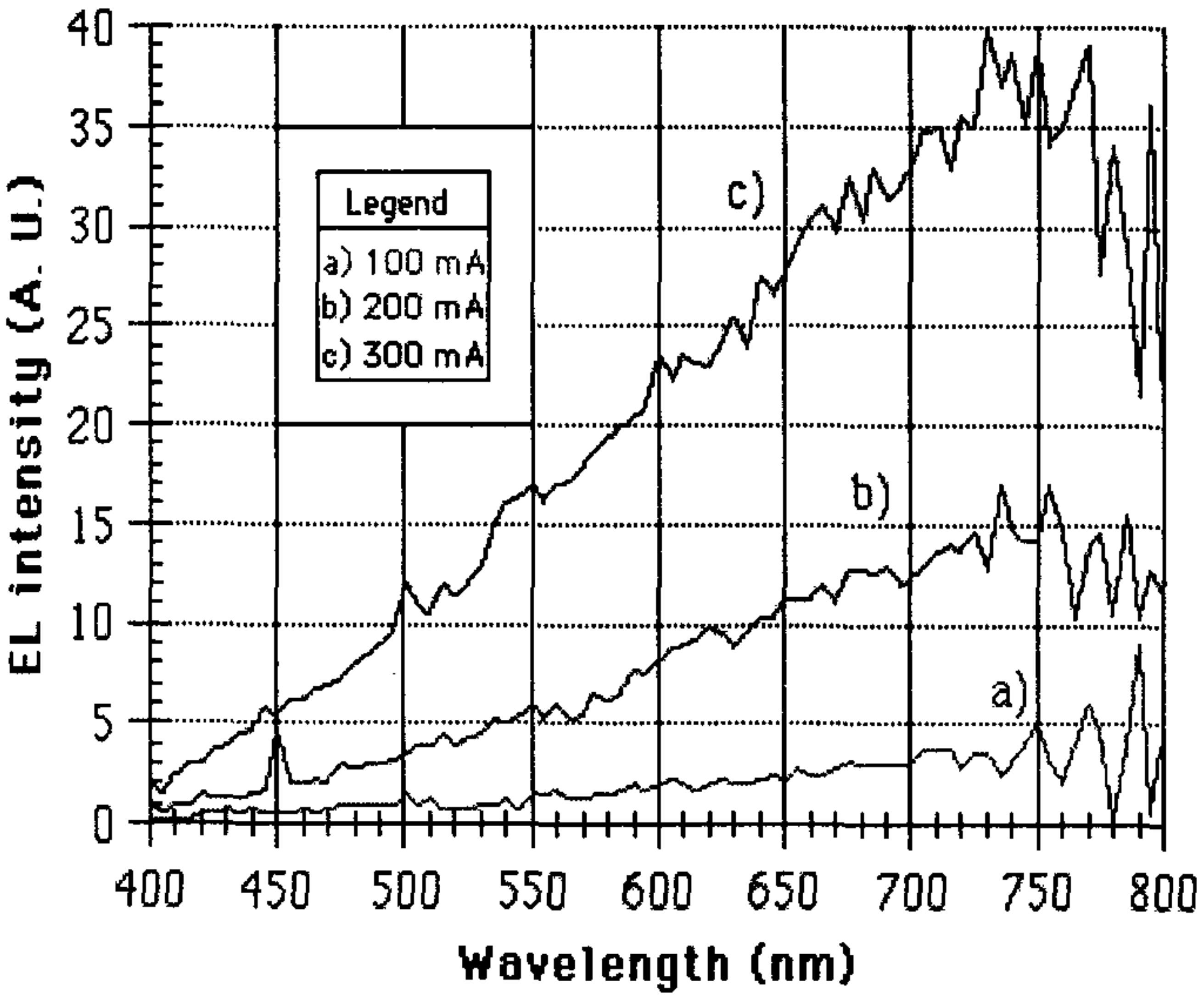

Fig. 4. EL spectrum for different currents through two adjacent electrodes at rever-se bias.

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Depending on PS anodizing regimes the emission peak can be both in the blue and in the red. But the emission spectra are very broad, with example which covers the whole visible range [18]. The other approaches are to be used for a color microdisplays to get a narrow light emission spectra, say, the integration of a PS LED with a PS microcavity [19].

If the current through the pads is related to the intensity of the emitted light a nearly quadratic dependence was found.

The special attention was paid to the response time of a PS LED. The transient electroluminescence waveform with the minimized response time is shown in Fig.5. The delay time of 1.2 ns and the rise time of 1.5 ns can be evaluated from the curve presented in Fig.5 for the voltage pulses of 12 V.

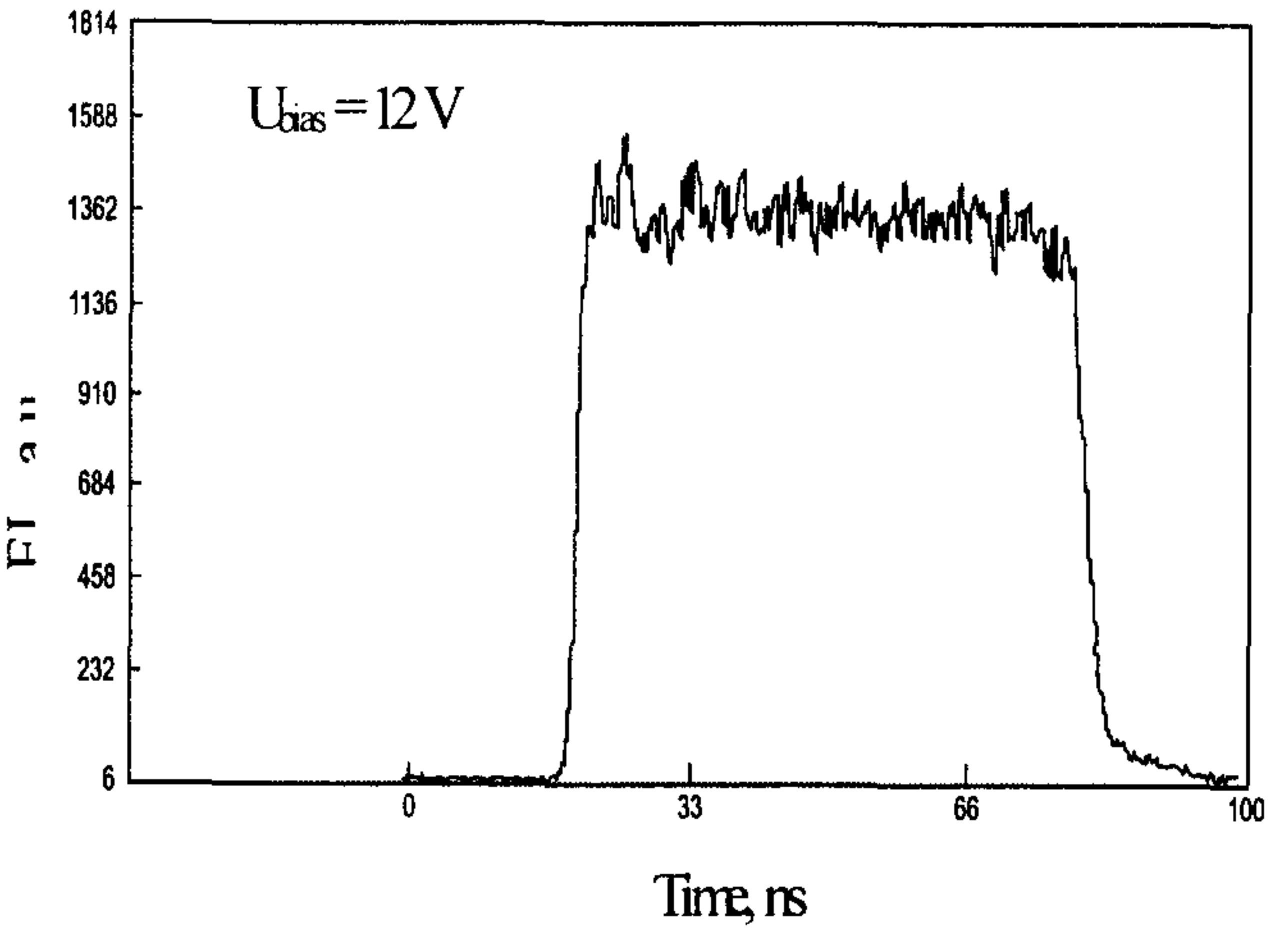

Fig.5. The rise and delay times for a PS LED.

The shortest response time was published for forward biased PS LEDs [20]. However, our devices are faster, because they have no diffusion capacitance. The main mechanism of minor carrier generation in reverse biased Al/ PS junctions is impact ionization at avalanche breakdown at high electric field. A regular columnar PS structure promotes the very fast avalanche breakdown due to non-uniform electric field distribution inside the PS layer [7]. The time of the avalanche response is estimated to be as less as 1 ps [21]. Thus, we have shown that our PS LEDs can operate in the nanosecond region. By further technology optimization, we hope to reach the sub-nanosecond range.

All fabricated samples demonstrated good reproducibility and stability even at high current densities. Their main parameters are listed in Table 1.

Table 1. Typical parameters of Al/PS LEDs

Parameter	Units	Value
Maximal quantum efficiency*	%	1.0
Optical power density	W/cm^2	0.1
Visual detection threshold	V	-4
Response time	ns	1.2
Frequency response	GHz	0.2
Minimal pixel size	µm	1x1
Estimated life time	h	>10000

* pulse operation

As can be seen from the Table 1 the PS LEDs are quite fast, so direct multiplex addressing can be applied. The resolution of Al/PS microdisplays can be as high as million pixels per 1 cm^2 that can not be achieved at present by other microdisplay technologies. In this case the pulse operating current for a pixel is varied from 1 to 10 µA, that corresponds to operating currents of silicon VLSI components.

The main disadvantage of PS LEDs is related to their low efficiency. Taken into account the reported quantum efficiency of about 1% (or power efficiency of about 0.3%), the estimated thermal load for a 100 Cd/m^2 PS LED is 0.3 W/cm^2. It is obvious that in this case the heat should be removed to prevent overheating effects. However, if the brightness is limited at the level of 20 Cd/m^2, the heat dissipation will not result in catastrophic overheating effects and a device can operate in continuous regime for more than 1000 h without any considerable degradation [22, 23].

5. Conclusions

The analysis of reverse biased PS LED developments for the last ten years has shown considerable parameter improvement towards practical implementtations of these devices in microdisplay technology. Bright and stable light emission was observed in Al / PS reverse biased Schottky junction. The time stability of light emission was quite high thanks to reliable passivation of porous silicon surface in the presented device construction.

Developed light emitting devices are totally compatible with modern silicon IC technology. Thus, Al/PS light emitting structures fabricated onto a silicon chip containing driving circuitry can solve many miniaturization problems for microdisplay technologies.

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6. References

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