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A Practical Porous Silicon Device Structure For Increased Electroluminescent Efficiency

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Abstract— This work reports on the results of two innovative designs for efficient silicon-based light emitting devices(LEDs). The two devices demonstrated improvement on the extraction efficiency of photons produced by electroluminescent porous silicon. With the previous structures, the produced luminescence was collected from the surface of the devices through the electrical contacting layers. The first new device uses a redesigned top contact along with an etch into the active region of the device. The second type used an edge emitting arrangement. The new surface emitting device showed visible luminescence that was easily seen in a dim ambient. The edge emitting structure exhibited an increase in intensity of between two and three orders of magnitude. This paper will not discuss the in depth physics of luminescence from porous silicon. Rather, it will only discuss the physical device structures and the strategies by which the emitted photons are extracted.

I. INTRODUCTION

The need for an efficient silicon-based light emitting device is crucial to the development of silicon-based optoelectronics. A complete system would consist of an emitter (the LED), a waveguide, and a detector. The material of porous silicon has been known for nearly 40 years. In the 1980s, several studies of the optical properties of porous silicon were published and, in 1990, bright red photoluminescence was detected by L. Canham(Fauchet). Research focus has since shifted toward studying the electroluminescent(EL) behavior. By passing current through the porous silicon (P-Si) region, injected carriers can radiatively recombine across the bandgap. The resultant photon has an energy approximate to that of the bandgap of the porous silicon. It must be noted that the energy bandgap of porous silicon is larger than that of crystal silicon due to quantum confinement which enables it to luminesce at visible wavelengths (Fauchet).

Light emitting porous silicon has the structure of intertwined columnar structures which maintain a crystal-like configuration and range from a few nanometers (high porosity-HP) in diameter to tens of nanometers (low porosity-LP) in diameter. To produce porous silicon a process known as anodization is performed. The Si wafer (anode) and a metal cathode are immersed in an aqueous solution containing HF. Current is then passed through the wafer and, in the presence of holes, HF dissolves the silicon into these columnar structures.

The previous porous silicon LED's have been of the surface emitting type. The devices were fabricated with a semitransparent conductive film as the top contact and electroluminescence was extracted from the surface of the device through, and around, the top contact. The efficiency of these devices is very low due, in part, to a poor method of extracting the emitted photons from the device. Many photons are absorbed by the substrate and contacting layers. The refractive indexes of the adjacent layers play a significant role in the loss of luminescence due to absorption. Figure 1 is a schematic of this device, illustrating the problems it has caused by refraction and absorbance. For efficient carrier injection into the porous region, an ohmic contact must be made to the porous silicon. Since HP P-Si luminesces more efficiently than LP P-Si, a contact directly to a HP region would be ideal. Unfortunately, due to the roughness of the porous silicon, a LP P-Si, Poly, Aluminum stack was necessary to achieve good electrical contact.

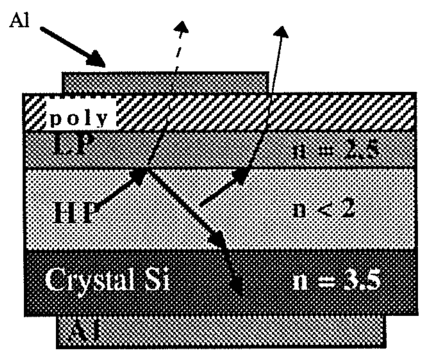


Figure 1: Previous surface emitting structure. Luminescence extracted through and around top contact..

It has been established that lower porosity silicon will allow a better polysilicon film to form and, hence, a better contact and more efficient carrier injection. It is for this reason that the previous device structure utilized a low porosity layer between the polysilicon and HP region.

II. INVESTIGATION

The strategy for the first new structure was to redesign the top contact of the previous structure and also, using the new top contact as the etch mask, etch through the polysilicon and

porous layers (Figure 2). This arrangement decreases absorption into the adjacent regions and improves the extraction of the emitted photons due to increased collection of scattered light.

The strategy for the second structure was that of an edge emitting configuration. This allows extraction of the emitted photons directly form the porous layers. This new structure which takes advantage of the differences in the relative indexes of refraction of adjacent layers.

As is discussed below (*Controlling Porosity and Index of Refraction of the Porous Regions*), the refractive index is inversely proportional to the porosity of the porous silicon and the porosity of the silicon can be controlled by the initial substrate doping before anodization is performed. By creating a low porosity layer sandwiched between two highly porous layers (cladding layers), a waveguide is produced which serves to "pipe" light out of the device. This new structure causes less loss to absorption by the substrate and electrical contacts. *Note: To achieve the structure and doping profile illustrated in figure 3, it was originally intended that a high-energy implant be performed, however, this was not possible. To achieve the doping profile of figure 3, a low energy implant with a short drive-in was performed followed by a polysilicon deposition which was subsequently doped to a low level*

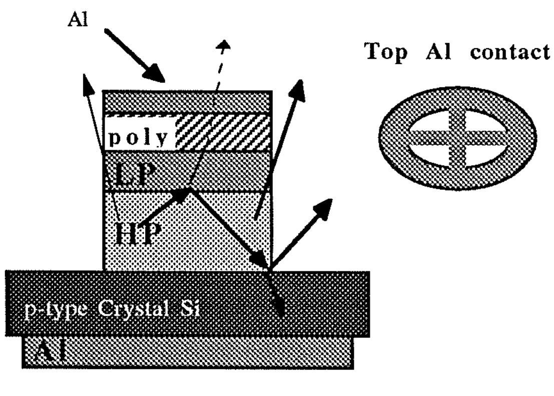


Figure 2: Improved surface emitting structure—Increased collection of scattered light and decreased absorption into the adjacent regions.

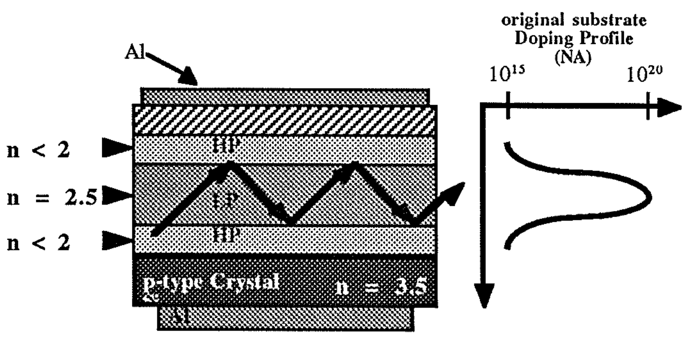


Figure 3: Edge emitting device

Controlling Porosity and Index of Refraction of the Porous Regions

Porosity is controlled by the dopant level of the substrate prior to anodization. The dopant level of the substrate and the resultant porosity are inversely related. Porosity and the refractive index of the porous silicon are also inversely related. Figure 4 shows the general relationships among Original dopant profile, resulting porosity, and the refractive index of the porous silicon. By the above relationships, a direct relationship between the original substrate doping, before anodization, and the refractive index of the resulting porous silicon is obtained. The result is that a larger refractive index of the resultimg porous silicon can be achieved with a larger substrate doping. *The Graphs of figure 4 represent general trends and have not been constructed from actual data.*

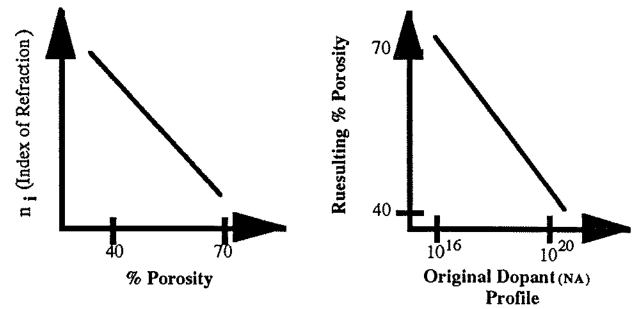


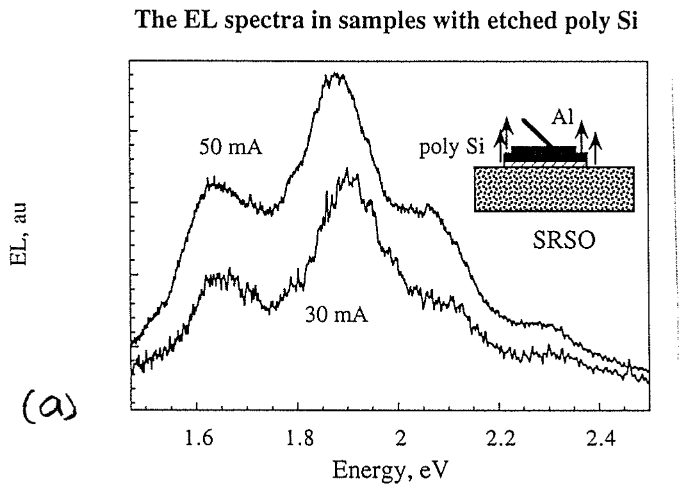
Figure 4: Trends relating Porosity, Refractive Index, and the initial dopant level of the crystal Si to produce a given level of porosity after anodization.

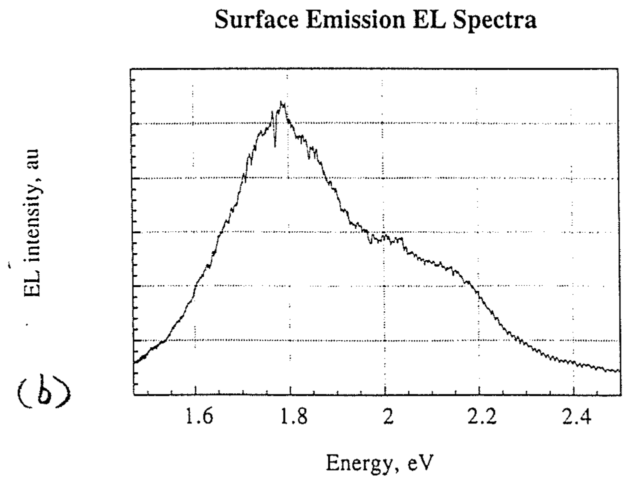
III. Results and Discussion

Tests of the improved surface emitting device showed an increase in luminescent intensity. The luminescence seemed fairly uniform over the entire contact region and easily visible in a dim room ambient. Prior devices arranged as the device of figure 1 had only displayed moderately visible luminescence in a narrow band around the perimeter of the top contact. The aluminum contact of the improved device may have been significantly thinner than the contact of the prior device.

Tests of the edge emitting structure showed a considerable improvement in the intensity of emitted radiation extracted from the device with an estimated increase of two orders of magnitude over the surface emitting structure. It must be noted that the emitted radiation emanated from a region roughly two micrometers in width and was not visible to the naked eye. A device of this size would, however, be of the size used in many practical silicon-based optoelectronic systems.

Normalized spectra from each of the respective device types is given below in Fig. 5. The EL spectral peaks of the devices occur at roughly 1.9eV(653nm), 1.8eV(690nm), and 1.55eV(800nm) for the previous surface emitting structure, improved surface emitting structure, and the edge emitting device structure. The multiple peaks in the spectra of the original structure are due to constructive and destructive interference patterns caused by reflections off of adjacent layers. The slight shifts in the peaks at different source currents is not well understood. It must be stated that slight process differences from the process of the original surface emitting device may have contributed to the significant increases in intensity yielded by the two new devices. More testing and experimentation is needed to determine which effects were responsible for the increases. Also, quantified values must be attached to the results.





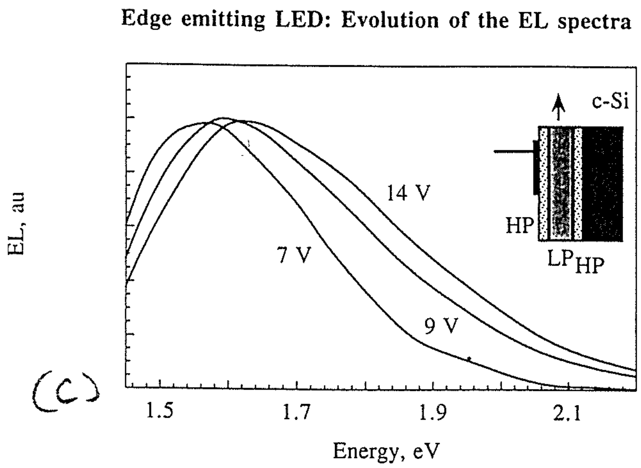


Figure 5: Normalized spectra for the (a) previous surface emitting device (b) improved surface emitting device (c) edge emitting device.

IV. Summary

Two new silicon-based light emitting devices were presented which exhibit increased intensity over the prior device arrangements. The first increasing the surface emittance and the second, extracting the emitted photons directly from the porous layers.

Acknowledgment

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References

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APPENDIX

	PROCESS	DC1	DC2	DC3	DC4	DC5
1	5 p-type wafers 10 ohm-cm					
2	Backside Implant (BF2, 2E15, 170 KeV)	X	X	X	X	X
3	Anneal Backside (1100C, dry O2 5lpm)	X	X	X	X	X
4	BOE	X	X	X	X	X
5	Implant (BF2, 1E15, 1E15, 100KeV)	X	X	X	X	X
6	Anneal (1000C, 15min, dry O2)	X	X	X	X	X
7	BOE	X	X	X	X	X
8	LPCVD (Poly-Si, 5000A)	X	X	X	X	X
9	Dope Poly with substrate (1000C, 20min, N2)	X	X	X		
10	Implant (B11, 2E12, 35 KeV)		X			
11	Anodize (1:1 HF:Ethanol, 300mA – 2x2 platinum foil as cathode)					X
12	Anodize (1:1 HF:Ethanol, 300mA – platinum wire cathode in solution)		X	X		
13	Anneal P-Si (Push 8 in/min - 900C, soak 950, pull 8 in/min - 900C – all in N2:O2 9:1)		X	X		X
14	LPCVD (Poly-Si, 2600A)		X	X		X
15	Implant (P31, 1E15, 50KeV)		X	X		X
16	Anneal (850C, 15min, N2, push/pull 10in/min)		X	X		X
17	Sputter (Frontside, Al, ~4500A) – DC2, DC3 shadow masked		X	X		X
18	Photo for Al contact					X
19	Al Etch and Ash					X
20	Sputter (Backside, Al, 5000A)		X	X		X
21	Sinter (425C, 25min, H2N2 - 5lpm		X	X		X
22	Etched Poly (SF6, 400mTorr)					X