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Cavity Effect in Nanocrystalline Porous Silicon Ballistic Lighting Device

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1. Introduction

Si-based electroluminescence (EL) is highly desirable for low-cost, VLSI compatible photonic devices, interconnects, or other applications requiring light sources. Red-band photoluminescence (PL) of nanocrystalline porous Si (nc-PS) can be highly enhanced and stabilized by appropriate surface termination[1,2]. Based on this approach, the EL emission has been much improved[3]. The EL efficiency, however, is still rather low from a practical level. Besides the low red EL brightness, the lack of green and blue EL emission is also a big subject to be solved.[4]

Diodes including nc-PS can also operate as surface-emitting ballistic electron sources in vacuum or air. This cold emission is due to generation of energetic electrons via multiple-tunneling transport through interconnected Si nanocrystallites[5]. Its application to display has been pursued, in which luminescent films placed either in vacuum[6] or directly onto the nc-PS layer[7] are excited by the energetic electrons. With the latter configuration, all solid-state multicolor EL has been achieved using different organic luminescent films[8].

In this paper, a new configuration of the ballistic EL device is proposed with a view to narrow the bandwidth of the EL emission on a basis of the cavity effect with the use of an inorganic luminescent film ZnS:Mn.

2. Experimental

The initial substrate consisted in a 3.2 μm-thick non-doped polycrystalline silicon film on n-type (100)-oriented crystalline Si (0.01 Ωcm). The nc-PS layer was formed in the polycrystalline silicon region by anodization in HF solution, following a procedure already described previously[8].

After anodization, nc-PS was thermally oxidized (900ºC, 30 min in O_2). Then, high-pressure water vapor annealing (260ºC, 3h, 1.3 MPa)[1,2] and annealing in forming gas (540ºC, 60 min) were perfomed in order to stabilize the nc-PS structure.

A 10 nm-thick Ag film was deposited onto nc-PS as the lower mirror of the cavity. Then, 294 nm-thick ZnS:Mn was deposited by electron-beam evaporation. The samples were then annealed at 600ºC for 60 min in Ar in order to activate the ZnS:Mn film. Finally, a 10 nm-thick Ag film was deposited as both the upper mirror of the cavity and the top electrode. The thickness of ZnS:Mn is chosen as half the peak wavelength of its PL emission in order to get a single mode optical cavity for emission at 597 nm. The final device is shown in **Fig. 1**.

The optoelectronic properties of the device were acquired at room temperature in N_2 gas ambient, in terms of the current-voltage characteristics, bias voltage dependence of the luminescence intensity, emission spectrum, and the dynamic response.

3. Results and discussion

Figure 2 shows that the device exhibits a rectifying behavior similar to the nc-PS diodes operating with organic films or under vacuum[8]. The onset of the EL was at about 7 V. Orange light is uniformly emitted and is visible with naked eye in room lighting at a forward bias voltage of about 15 V. The EL-current curves corresponding to Fig. 2 are shown in **Fig. 3**.

Significant EL emission occurs mainly under forward operation. This is because the ballistic electrons impinging into the luminescent ZnS:Mn film can be generated efficiently only under this polarization. Electrons injected from the Si substrate into the nc-PS layer are drifted toward the top contact by the applied electric field. Some of them become quasi-ballistic by multiple tunneling through thin oxide films between Si nanocrystallites. The kinetic energy acquired by those electrons is high enough to excite the ZnS:Mn film. Th is consistent with

In conventional EL devices where inorganic films such as ZnS:Mn are used, oxide layers are used to enhance the field effect. In our case, the highly energetic electrons are generated by the nc-PS layer.

If the luminescent film is sandwiched between two mirrors, an optical resonance occurs at the wavelength corresponding to twice the film thickness. This is known as a Fabry-Perrot resonator. **Figure 4** shows the EL obtained with the device shown in Fig. 1. For comparison, the PL of a single ZnS:Mn film is also shown. The EL spectrum is clearly narrower than the PL one, showing the effect of the cavity operation. Since the cavity structure was designed such that the resonance wavelength matches that of the PL peak, the EL peak wavelength properly coincides with the the PL one. In addition to the optical effect, the lower Ag film also acts as an equi-potential plane. This results in a high uniformity of the emitted EL over the whole contact area.

The present results show the possibility of cavity resonance in ballistic devices. A narrower EL spectrum would be expected from a more complete cavity structure. Especially the mirrors' reflectance of the cavity and their flatness should be improved to enhance the resonance effect. The roughness of both the nc-PS layer and the ZnS:Mn film should also be suppressed. The optimization of these device parameters, including the appropriate control of processing conditions, would make it possible to enhance the resonant feature of the EL emission.

4. Conclusions

A light-emitting device based on nc-PS acting as energetic electron generator and ZnS:Mn as luminescent film was presented. Efficient and uniform orange EL was observed at relatively low bias voltages. Furthermore, a cavity built using two Ag mirrors on both sides of the ZnS:Mn film operates well and effectively narrows the EL spectrum. This device is very attractive as a all thin-film surface-emitting light source for various applications.

Acknowledgements

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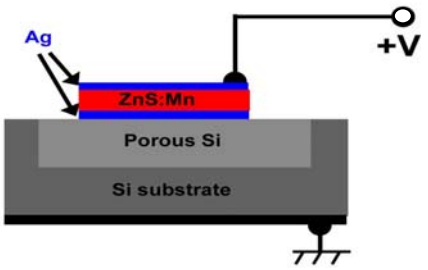

Fig. 1. Schematic representation of the solid-state light-emitting device using a luminescent ZnS:Mn film sandwiched between two Ag semitransparent films in order to form an optical cavity.

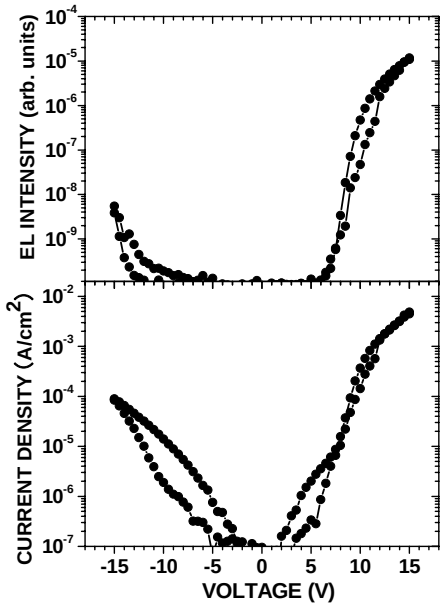

Fig. 2. Current density and EL intensity as a function of applied voltage for the device shown in Fig. 1.

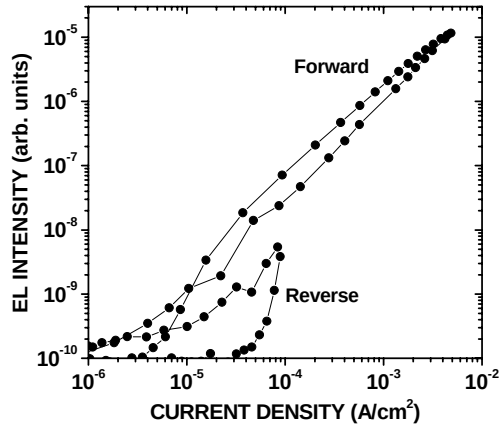

Fig. 3. The EL intensity as a function of driving current density.

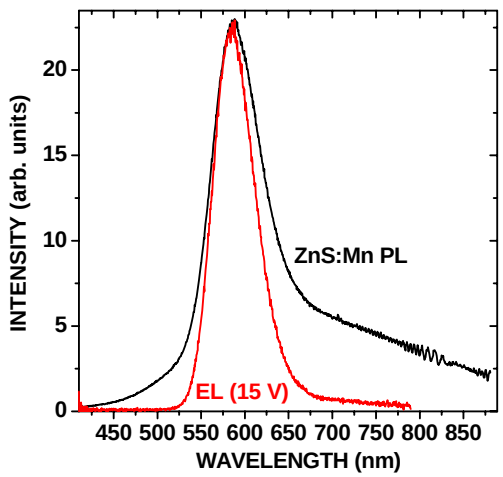

Fig. 4. PL of a ZnS:Mn single layer and EL at 15 V of the device shown in Fig. 1, including a cavity structure to narrow the EL spectrum.