Microcavity Effects in Thin Film Electroluminescence

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Using Fabry-Perot structures by sandwiching Thin Film ElectroLuminescence (TFEL) stacks between mirrors the emission can be confined spectrally and/or angularly to the Fabry-Perot modes. Even for active films optically as thick as 15 quarter wavelengths appreciable spectral narrowing of broad emission bands (ZnS:Mn) has been observed, as well as angular confinement in the case of narrow lines (ZnS:Tm, Ho). Comparisons with first attempts of modelling have been made.

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Microcavity effects in thin film electroluminescence

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INTRODUCTION

Microcavity effects have recently been identified in organic electroluminescence (EL) LEDs[1], in surface emitting III-V LED structures[2], and even in some electrically passive optic devices[3]. Very recently even tunable microcavities have been reported[4]. The common understanding is that the final (photon) state density determining the transition probabilities of excited ions in Fabry-Perot structures[5,6] leads to a drastic rearrangement of radiation patterns along the mode structure and to an increase of up to 100 % in oscillator strength. A broader perspective has been given in review articles[7,8], covering possible applications.

From all this research one would expect to see some similar effects in inorganic thin film EL. However to our knowledge this is the first detailed report about those effects, and about effects in quite large (practical) cavities. An understanding of the quantitative influence of mirror design especially on off-normal mode emission is almost totally lacking, and the questions of what layer has to be included into the mirror design and what has to be regarded as fill of the Fabry-Perot, is controversial. Our approach did not differentiate between these questions, but was a full stack approach using well established thin film design tools.

EXPERIMENTAL PROCEDURES

The samples prepared were of rather conventional design: dielectric multilayer mirrors were deposited on a glass substrate by e-beam evaporation, using standard optical coating systems. After assuring the wanted optical behavior of the dielectric mirror by wideband transmission measurements, the EL stack was deposited onto the 4" wafers in a system with high thickness predictability for each single film. Several host/dopant combinations were used for the active films. On some samples both the in-process thickness

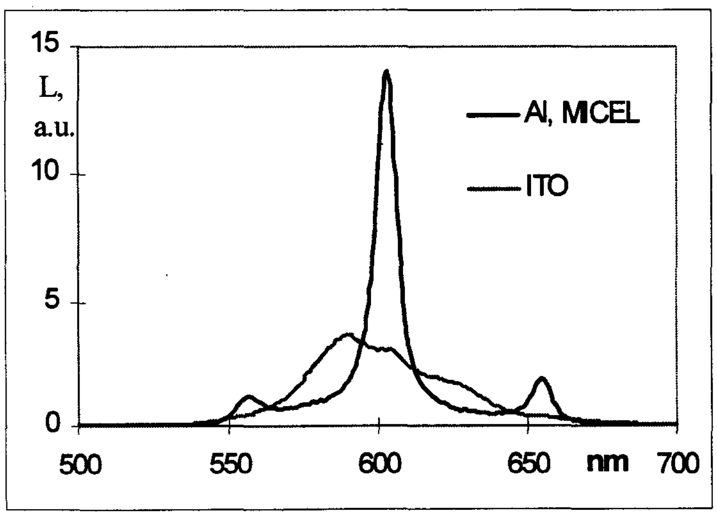
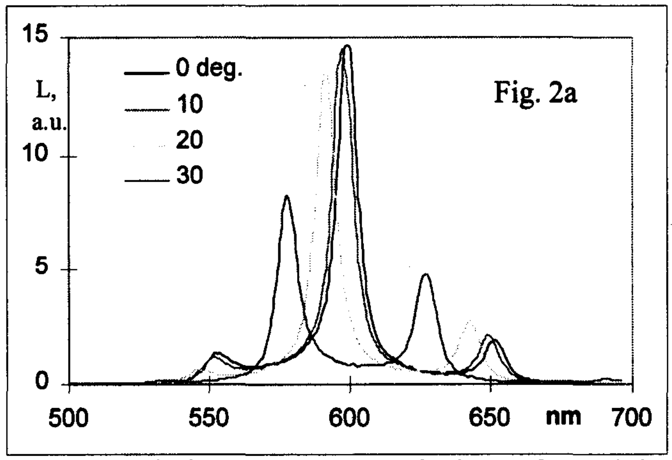


Fig. 1: Comparing the microcavity narrowed spectral emission with the interference modulated radiance from a nearby ITO contacted test area.

monitoring and wideband transmission measurements were done after the deposition of each individual film to confirm the development of the wanted optical properties.

The last preparation step was the structuring of electrode patterns into Al and ITO, deposited side by side on top of the stack. The ITO top electrodes defined reference samples with no Fabry-Perot influence. Emission spectra were measured on both types of samples under various angles, at carefully controlled input of the same power density into cavity and non-cavity areas sitting close to each other on the same wafer. This cautious procedure appears necessary to exclude erroneous conclusions, that might arise from the comparison of noncomparable samples. An example of a concise comparison is shown in Fig. 1 for the ZnS:Mn EL.



In most cases, besides the two types of samples on the same wafer in the same deposition run, additional samples were prepared on ITO on glass, using a top Al electrode. They acted as additional reference samples. They were mainly used to do a quantitative comparison of the total emission using an integrating sphere. Under exactly equal input power the emission spectra were quantitatively compared using an optical multichannel analyzer.

RESULTS AND DISCUSSION

As Fig. 1 shows, an appreciable spectral narrowing is the consequence of microcavity action on EL (MiCEL). The position of the peak coincides within 6 nm with the design expectation. The much broader emission spectra of the test area with the ITO back electrode exhibits some interference effects, but clearly shows no narrowing compared with the well-known ZnS:Mn emission. In this case the designation 'micro'-cavity is an exaggeration: the optical thickness of the active film is 13 quarter-wavelengths (QWOT). However, this might be seen as an advantage for practical purposes.

Measuring the change of the spectra with angle, Fig. 2a was obtained. The shift to smaller wavelengths for higher angles is expected from elementary reasoning.

A comparison with simulations is shown in Fig. 2b. For this purpose the "free-space" Mn emission spectra, which is shown on the figure, was reestablished,

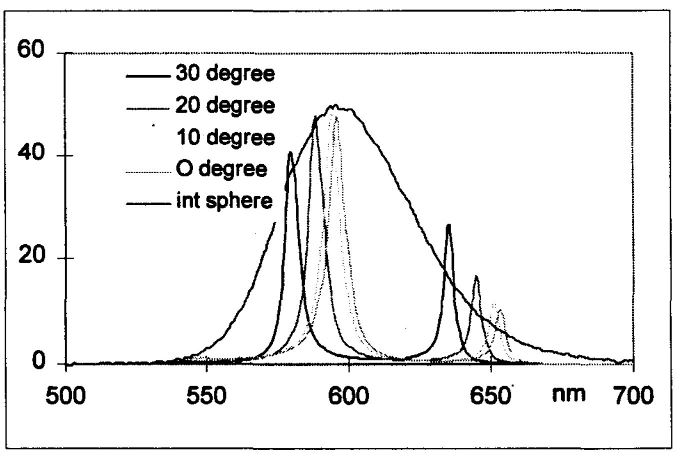


Fig. 2: (a), upper part: Spectral distributions measured under different viewing angles from a MiCEL, using ZnS:Mn as active material; (b), lower part: simulations of angular dependencies of spectra by multiplying a ZnS:Mn "free-space" emission curve by (1-R), with R being the reflectance of the whole Fabry-Perot, as calculated from design data.

using an integrating sphere and the ITO test area of the same sample. Multiplying this curve with data calculated from the design, the curves of Fig. 3 were obtained. The comparison indicates, that there is room for improvement, but it has to be emphasized that using (1-R) as measure of the relative enhancement of emission in a cavity is just a first trial.

Using ZnS:Tm as the active material in the EL stack and doing the main investigation on the dominating IR line emission at 800 nm, Fig. 3 was recorded. Within the narrow emission band a very similar spectral shift has been obtained, and outside this angular region negligible emission was found. It is therefore fair to say that an angular narrowing is the major action of the Fabry-Perot. Considering the fact that on a reference sample an essentially Lambertian distribution was measured, an increase in the radiance per steradian of about a factor of 10 was obtained. Fig. 4 displays spectra measured by using the angularly integrating action of an integrating sphere on a MiCEL and its reference sample, which had ZnS:Ho as active material and were prepared in the same TFEL stack deposition run. A rather good match of the spectra is achieved both in shape and in absolute power. The fact that the absolute values of radiance are about 35% lower in the case of the MiCEL is tentatively attributed to the losses in the Al back mirror, which multiply by the times of the multiple reflections. A five times reflection would explain the quantities.

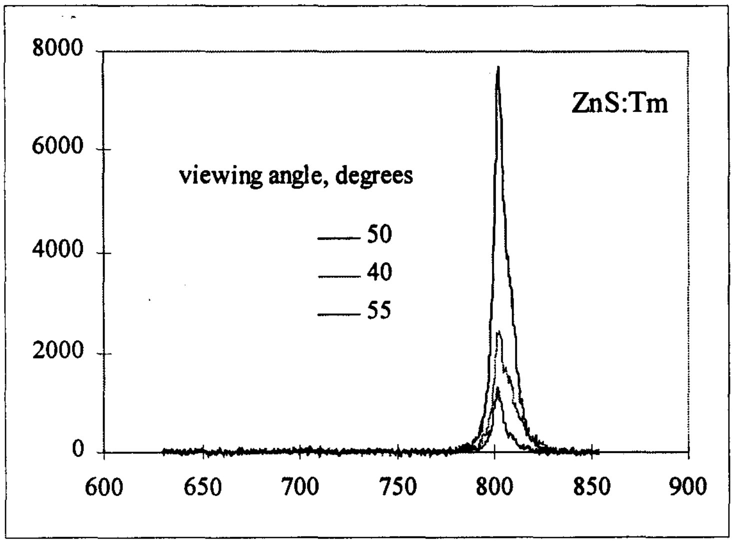


Fig. 3
By a deviation of the actual thickness of the active ZnS:Tm film from the design value a very interesting sample was obtained, emitting into a hollow cone, 50^0 off normal

CONCLUSIONS

TFEL stacks deposited with usual methods onto dielectric mirrors, which are highly reflective in the spectral region, in which the emission of the TFEL normally occurs, can give rise to microcavity action if the top electrode is highly reflective too. In all cases reported here the top electrode was from Al. In order to achieve appreciable radiance the EL stack has to be on the order of 0.5 to 1µm. This renders the cavity no longer "micro" in the sense of carrying one mode only. Thicknesses checked range from 5 to 15 QWOT. In the case of spectrally broad emissions - ZnS:Mn - a drastically spectral narrowing is the most prominent feature. The peak of the emission shifts with increasing angle of observation to smaller wavelengths; neighboring modes might enter the broad emission profile.

In the case of spectral narrow emissions -ZnS:Tm - the emission is confined to a narrow cone. If the usual design goal of having the emission concentrated around the face normal, is not met, a hollow cone results.

Rather instructive is the behavior of a multi-line emitter, such as ZnS:Ho. Different modes may coincide with different (free space) lines, giving rise to a variety of angularly changing emission patterns.

By using reference samples and integrating spheres to reliably integrate the emission over the whole 2π space, we could show that no appreciable loss of light occurs. The loss encountered is tentatively attributed to the back Al mirror, which of course is far from being lossless. Multiple reflections can aggravate the situation of non-perfect reflectance.

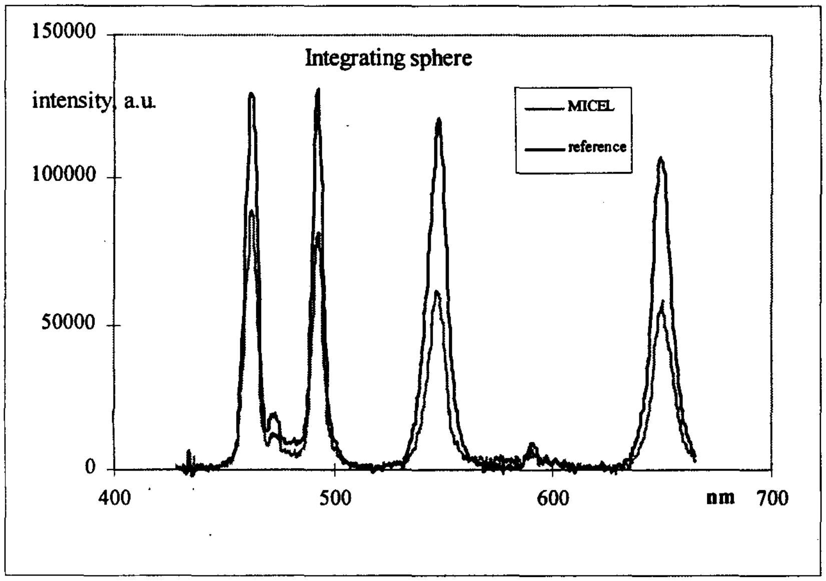


Fig4.
Emission spectra of a MiCEL and its reference sample measured "through" an integrating sphere under equal drive and at equal geometry and sensitivity factors. MiCEL action does not cut spectral parts off, but only redistributes angular distributions from free space ones.

ACKNOWLEDGMENT

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