High Luminance from Thin Film Electroluminescence Devices

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Thin Film ElectroLuminescence (TFEL) can be used for many applications besides displays. Most of them demand high brightness/radiance. Coping with the problem of thermal dissipation by reducing the duty cycle the radiance limit is set by efficiency and its decrease by dopant saturation. No other mechanism could be identified except for ZnS:Mn, which shows nonlinear cross-relaxation between closely spaced excited dopants. Values of 50 mWcm^-2 (40,000 cdm^-2) for face emitters and 1 Wcm^-2 (1,000,000 cdm^-2) for edge emitters appear to be the practical limits, without the reasons clearly identified.

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INTRODUCTION

Thin film electroluminescence (TFEL) can be useful in many applications besides and beyond displays. However most of these applications require the device to radiate high brightness or high light power. In the most general case, the TFEL device can be regarded and used as a two-dimensional *(planar)* or a one-dimensional *(line)* light source. Planar sources are often called *face* emitters, line sources are designated *edge* emitters. TFEL applications range from illuminators for object recognition, switchable radiation standards, printers or scanners to measuring tools, since they are easily structurable by photolithography to patterns of spatially constant radiance or irradiance, that are otherwise rather difficult to obtain. In many of these applications one can profit from the fast switching under adjusted drive conditions.

Given a certain efficiency, the luminance level is given by its product with the input power. However, this level is ultimately limited by thermal considerations, as increased temperature promotes degradation and in many cases demotes efficiency. Although heat sinking will be a problem, it will not be addressed here. In order to avoid this highly important, but secondary problem, we will limit our investigation to pulsed operation, in which the average power is below thermal margins. In many cases this mode is dictated by the application anyhow.

The primary question addressed in this investigation is whether there is any inherent limitation of luminance by a (nonthermal) decrease of efficiency with increasing drive.

Luminance levels up to 200,000 cdm^{-2} have been achieved from line, 50,000 cdm^{-2} from planar emitters. Light pulses as short as 1 μs are possible, using materials in which the current flow time determines the timing, as the radiative decay time of the dopant is short against it. As space is limited, we will restrain ourselves to some distinct behaviors, which, however, are typical for classes of dopants.

RESULTS

Experimental procedures

In this study we chose to increase the frequency, and often values up to 150 kHz have been used, usually in bursts, with relatively long periods in between, to avoid heating. For a given frequency the energy input per period, p, was varied by adjusting the drive voltage; typical values were - $p < 1.5$ mWs/cm^2, transferred charge $Q < 3$ $\mu C/cm^2$. It turned out that there is no big difference between the use of bipolar pulses and sine waves, although pulses provide more defined conditions in the low frequency reference situation, since they do not give rise to long current flow times. In order to assess the input power, either the transferred charge per pulse (half-period) or the energy per period was controlled and the latter was measured by taking the integral over the product of applied voltage and total current. The uppermost trace of Fig. 1 shows the voltage on a sensing capacitor as an example for charge monitoring.

The radiance was measured using a photomultiplier, calibrated against a low frequency, steady-state measurement with an NBS traceable spectro-photometer (Pritchard). In the case of multi-line emitters, only one line was monitored, but the shape of the spectra was checked for changes at various drive levels (only minor changes were detected) using a gated optical multichannel analyzer. In the case of edge emitters, the power from the edge, which is of only 0.5 to 10 µm height, was usually measured integrally with a large area detector, but care must be taken, not to allow the face emission to reach the detector. More sophisticated arrangements include acceptance angle defining imaging optics, but these are beyond the scope of this paper.

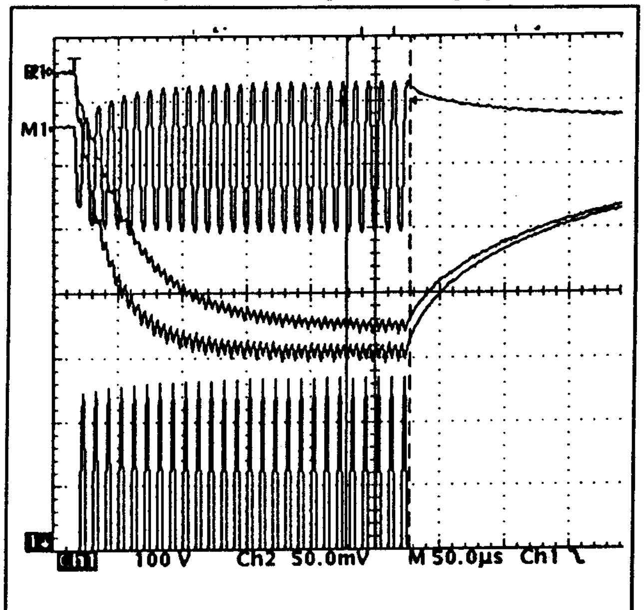

Fig. 1: Illustrating the experimental technique on ZnS:Mn: upper trace - transferred charge; middle traces - radiance; lower - applied voltage (partly visible). Slow but strong excitation build-up.

As mentioned above, to avoid heating the voltage was applied in bursts, which implies that the radiance built up gradually over time. In any case the stationary value approached at the end of the burst will be given, if no time dependence is displayed.

The TFELs used in this study were of the double dielectric sandwiched type on glass substrates. The face emitters used ITO as one transparent electrode, and the test areas were 2 mm by 2 mm. In general, radiance is proportional to thickness of the active film of the TFEL, if samples are operated at the same transferred charge, with the power input rising in the same manner. However, shooting for high ultimate radiance should be done on thick active films. The ones we used were about 1 µm thick. Using rough surfaces somewhere in the stack, improves the outcoupling of light, but supposedly the excitation saturates at the same level.

Results on face emitters

ZnS:Mn: Since it exhibits the highest reported efficiency, ZnS:Mn was one of the first candidates tested for the highest luminance, or better for the highest radiance. However it turned out, that strong nonlinearities in the dopant system - cross relaxation of neighboring excited ions - limit the luminance at arbitrarily high drive to about 60 $mWcm^{-2}$ or 50,000 cdm^{-2} (assumed Lambertian) in the planar case for a rough sample of about 1 µm thickness, as was partially known[1]. An example of a sample with smooth surfaces is given in Fig. 1, which shows the charge as the uppermost trace, measured on a capacitor of 90 nF, two radiance traces, and part of the 100 kHz voltage burst, driving the sample. The higher

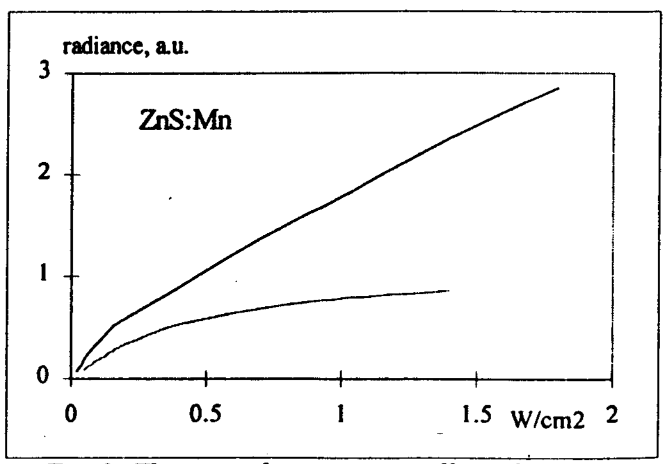

Fig. 2: The special saturatiopn effect of ZnS:Mn depends strongly on the Mn concentration, lower curve - $2.2*10^{20}$, upper - $1.6*10^{20}$ cm^{-3}

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radiance, 6.5 $mWcm^{-2}$, corresponds to the other conditions depicted; the lower to 65 % of the power input. Only a slight ripple remains of the pulse excitation; the slow decay of Mn gives rise to a dramatic pile-up of excitation. Rather different behaviors can be encountered, mainly depending on the Mn dopant concentration. Two examples are given in Fig. 2 for c.w. drives up to 2 W/cm^2.

ZnS:Pr: The fast decay of the Pr^{3+} emission makes it a good candidate to avoid excitation pile-up. However not more than 10 mW/cm2 could be obtained from non-optimized samples at 100 kHz. Sine wave drive was used. An appreciable modulation, of the radiance persists, more than 35 % of the peak, but further increase in drive to 150 kHz increased the mean radiance only by 10%.

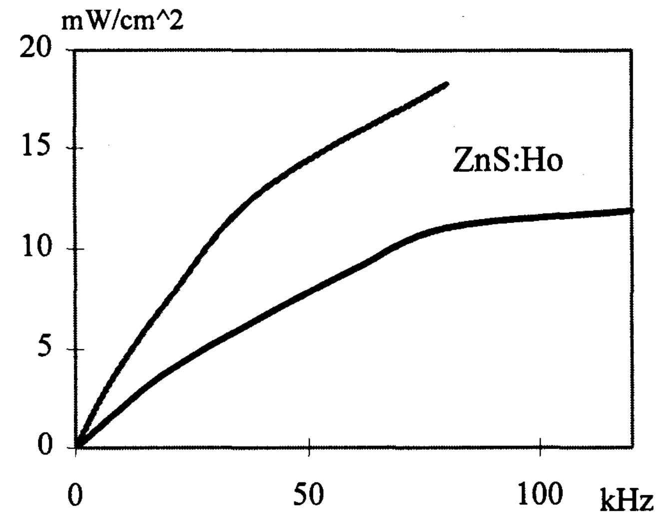

Fig. 3: ZnS:Ho starts to saturate at about 12 mW/cm². The upper curve was obtauined at an energy input of 0.4 mWs/cm² per period, the lower at half of that

ZnS:Ho: This material has moderate decay times, and reaches the same radiance level as ZnS:Mn at 2 W/cm^2 power input. Fig. 3 gives the dependence of radiance on the drive level, which was established by keeping the energy per pulse period constant. It is the most linear dependence obtained in this study. Again, we have a situation under 120 kHz pulse drive in which the ripple of the radiance of 12 mW/cm^2 is only about 5%.

ZnS:Tm: While it is unanimously agreed, that the blue emission is low, the efficiency of the infrared emission around 800 nm is fairly high and, as it stays constant with drive even beyond 10 W/cm2, it crosses the ZnS:Mn one. Decay time is medium, but at 100 kHz ripple is small. An unexplained rather slow build-up of radiance during the burst has been observed. Maximum radiance levels of 5 mW/cm^2 have been achieved.

Edge emitters

In the case of edge emitters, 300,000 cdm^{-2} from ZnS:Mn were reported years ago by Kun et al.[2] under steady state 3 kHz pulse excitation at the 2 W/cm^2 level. In fact, the values are geometry dependent, and supposedly apply to 0.1 mm wide edges. In a burst mode up to 1,000,000 cdm^{-2} appear possible.

The geometry limitations, which are not discusssed here, come about from the light guiding/spreading in the whole plane of the film stack, which thins the (inner) radiance out as 1/r, with r being the distance from the emission point.

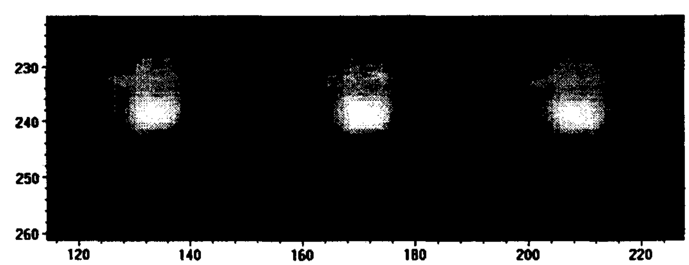

Fig. 4: Light distribution from a light guide capped 2000 dpi pixel; scale is 1.1 μm/division.

However, light guiding in a capping material on top of the stack (a topic of several patents to mostly Japanese inventors), can improve the transport and summing of light in a similar way as in a solar collector. The non-imaging optical enhancement device is not subject to the radiance limitations of imaging optics, and radiances beyond 10^6 cdm^{-2} appear possible. Strong confinement of light to small lengths of the "line" can be achieved. An example is shown in Fig. 4, which displays the light distribution from the end face of a 20 μm (wide) by 7 μm (thick) by 500 μm (long) light guide.

DISCUSSION

Driving of TFELs with increasing frequency, keeping the electric energy input per period constant, leads to an almost linear increase in brightness or radiance up to an level where excitation pile-up starts. An obvious and long known exception is ZnS:Mn, where the existence of a second excited level about 2 eV above the first one leads to strong quantum mechanical energy transfer (cross relaxation), that populates the second excited state, as soon as excited Mn ions get close enough to each other [1].

In the case of Ln^{3+} ions, no mechanism yet been proposed, to explain saturation. No change of decay time - shortening - points towards new non-radiative processes, developing at high drive conditions.

In the case of ZnS:Ho, which is relatively low doped, we estimated the fraction of exited dopants to be about 10 % at most at the highest reached radiance levels. It is difficult to understand a more than 10 % decrease of the differential efficiency from that. However, all estimates of this kind assume homogeneous conditions, large deviations form which are not unlikely[3].

CONCLUSIONS

TFEL can provide light sources for a variety of purposes in which planar or linear sources of lithographically determined dimensions of high radiance are wanted. As one of the most important findings, it turned out that the performance of the dielectrics is critical under high voltage, high frequency drive. Loss-free materials are absolutely mandatory. Except for ZnS:Mn, no process besides dopant saturation has been identified in this study. Therefore it is well possible to reach even higher radiance levels internally as well as externally under higher drive. In many cases some modulation of light pulses (burst length) does no harm, and the relatively low duty cycle allows for meeting the limits of thermal load on glass substrates. The extreme ruggedness and the temporal and environmental stability of these light sources are essential advantages over others in a variety of applications.

ACKNOWLEDGMENT

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