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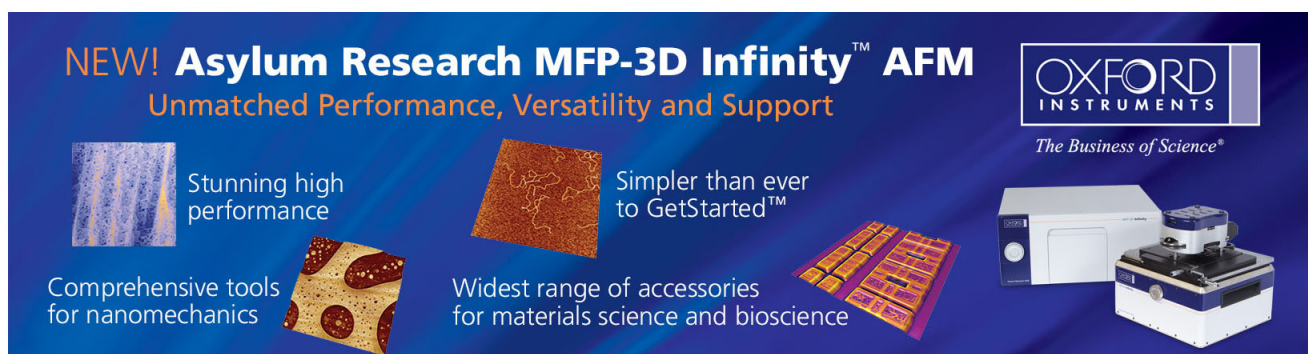J. Appl. Phys. **105**, 084508 (2009); 10.1063/1.3097276

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# Integration of polymer light-emitting diode and polymer waveguide on Si substrate

Yuan-Yu Lin, Chung Cheng, Hua-Hsien Liao, and Sheng-Fu Horng
*Department of Electric Engineering, National Tsing Hua University, Hsinchu 300, Taiwan, Republic of China*

Hsin-Fei Meng[a)]
*Institute of Physics, National Chiao Tung University, Hsinchu 300, Taiwan, Republic of China*

Chain-Shu Hsu
*Department of Applied Chemistry, National Chiao Tung University, Hsinchu 300, Taiwan, Republic of China*

We integrate a polymer light-emitting diode (PLED) and a polymer waveguide on a Si substrate. The light emitted from the PLED is coupled to the waveguide by a diffuser and a reflection layer with coupling efficiency about 1%. There is no delay nor distortion between PLED emission and the light propagation in the waveguide. Good direct modulation characteristics of the waveguide output are demonstrated up to 200 kHz. The device structure and processes are based on easy spin coating and are compatible to Si technology. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2219718]

Silicon is the most important material for modern integrated circuits. It is suitable for semiconductor electronic devices but difficult to be applied to optical devices due to the indirect band gap. Therefore to integrate optical devices on Si substrate becomes a highly desired but challenging subject since the concept of optical-electronic integrated circuits (OEIC) was proposed to solve the interconnect problem in high-speed computer chips.[1] Many efforts have been devoted to demonstrate the possibilities of OEIC on Si substrate such as using porous Si,[2] GaAs,[3] GaN,[4] InGaN multiple-quantum well,[5,6] GaSb quantum dots,[7] europium silicate layer,[8] and metal-insulator-silicon light-emitting diode.[9] However, these devices require expensive and complicated processes like molecular-beam-epitaxy and chemical-vapor-depositions technologies, which both need ultrahigh vacuum environments ($<10^{-7}$ Torr). In addition, most of these methods involve processes that are incompatible with standard very large scale integrated (VLSI) fabrication technology and the process integration becomes difficult. Recently organic materials attract some interests for OEIC applications due to its high luminescence efficiency and simple fabrication. Small-molecule light-emitting diodes (OLED) have been integrated on Si substrates as the light source[10,11] by thermal evaporations. Although the OLED has been integrated with a polymeric optical waveguide substrate,[12] this integrated device needs a special 45° cut mirror previously buried into the waveguide to reflect the light output from the OLED to the waveguide. The mechanical mirror cutting is, however, in great conflict with the standard VLSI fabrication technology. Another class of highly luminescent organic material is conjugated polymers. The spin-coating process makes conjugated polymer light-emitting diodes (PLED) much cheaper and simpler to fabricate than OLEDs. The spin-coating process is a well-developed technique in Si technology and is widely used for photoresist deposition. Therefore using

PLED on Si substrate to make OEIC devices has intrinsic advantages. Instead of the difficult 45° mirror, light coupling from PLED to waveguide is simply achieved by a diffuser with $SiO_2$ particles with 50–60 $\mu$m diameters dispersed in a photoresist. Because the size of the $SiO_2$ particles is much larger than the PLED emission wavelength, efficient light scattering is expected due to random reflection on the particle surface. Both the PLED and the waveguide coupling are easy to fabricate and fully compatible with standard Si technology. In this work we integrate a PLED and a SU8 polymer waveguide to demonstrate a OEICs device on silicon with good modulation characteristics up to 200 kHz.

Figure 1 illustrates the device structure. First, a 1500 Å Ag reflection layer is deposited on a cleaned Si substrate by thermal evaporation. Commercial $SiO_2$ particles (500 mg)
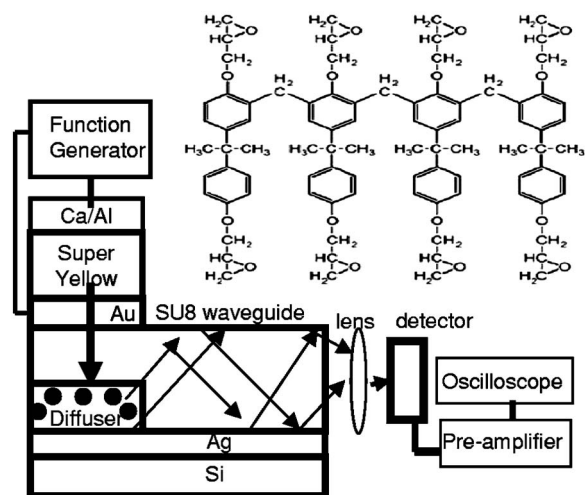


FIG. 1. Integrated PLED and SU8 (chemical structure shown) waveguide device on Si substrate. When PLED is turned on, the light passes through the transparent Au anode layer and propagates in the SU8 waveguide due to diffuser scattering and Ag reflection. The measurement configuration is also shown.

a)Author to whom correspondence should be addressed; electronic mail: meng@mail.nctu.edu.tw
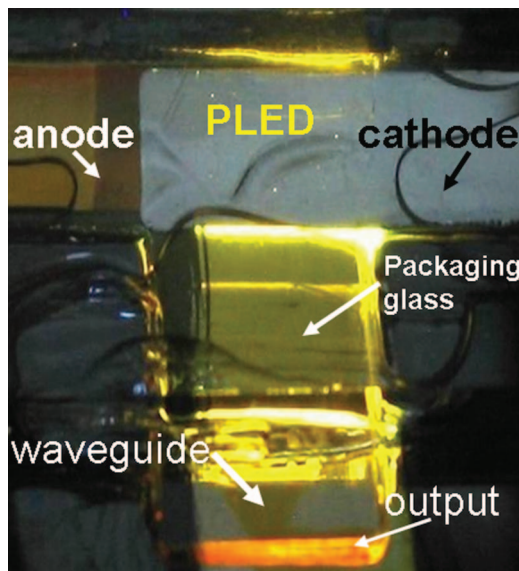
FIG. 2. (Color) Picture of the working integrated device. The light is emitted from the PLED and propagates in the waveguide. The output from the waveguide is redshifted relative to the PLED due to the scattering in the waveguide. The light at the end of the waveguide is the desired signal. The total coupling efficiency from PLED to the end of waveguide is about 1%.
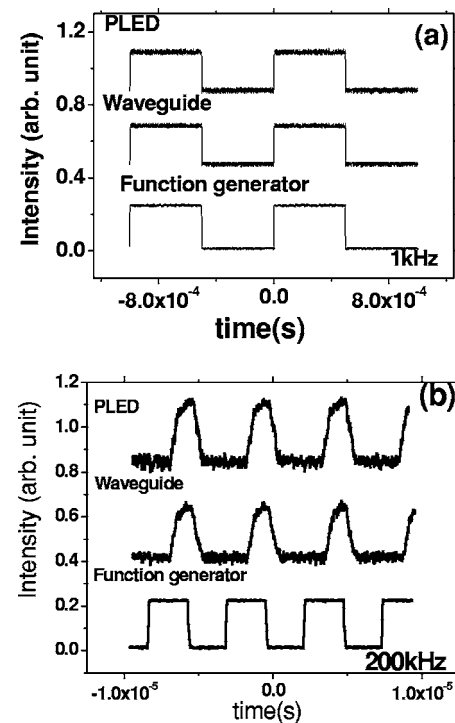


FIG. 3. The modulation characteristic of the light from the PLED, waveguide, and reference electrical signal. (a) Modulation at 1 kHz. (b) Modulation at 200 kHz.

and poly(methylmethacrylate) (PMMA) (90 mg, with molecular weight 965 000 purchased from Gredmann) are dissolved in chlorobenzene (2910 mg) to form a diffuser solution which is spin coated on the Ag reflection layer. Such $SiO_2$ concentration is the saturated value, beyond which uniform dispersion becomes impossible. Light scattering efficiency is found to be not very sensitive to the $SiO_2$ concentration. Acetone is used to remove the diffuser outside the PLED active region. Afterward the substrate is baked at 65 °C for 5 min and further baked at 95 °C for 10 min to remove the chlorobenzene. After the diffuser layer is dried, NANO™SU8 2050 (purchased from MicroChem) is spin coated on the substrate and baked at 65 °C for 5 min and then 95 °C for 3 h to remove the solvent and form a 100 $\mu$m SU8 layer. SU8 layer is exposed under a *i*-line (365 nm) aligner with a shallow mask which defined the waveguide patterns. This exposure process generated a strong acid, which would be used to drive epoxy resin to crosslink by a post exposure bake at 65 °C for 5 min and then 95 °C for 3 h. The patterns are developed with MicroChem's SU8 developer and the SU8 waveguide is completed. After the waveguide fabrication a PLED device is fabricated. A 200 Å Au layer is evaporated on the SU8 waveguide to form a transparent anode, and 0.6 wt % Super-Yellow polymer (Covion Organic Semiconductors GmbH; now Merck OLED Materials GmbH) dissolved in toluene is spin coated on the Au anode, forming a 700 Å emissive layer. Finally, a trilayered cathode (20 Å; LiF, 350 Å Ca, 1000 Å Al) is deposited and the PLED is packaged in a glove box.

When PLED is turned on, the light passes through the transparent Au anode to the SU8 waveguide due to the scattering by the diffuser as showed in Fig. 1. If light reaches the lower boundary of the waveguide, it will be reflected by the Ag layer such that the absorption by Si substrate is prevented. Therefore part of emitted light can propagate in the waveguide. Figure 2 shows the picture of the working integrated device. It is clear to see that the light indeed comes out from the end of the waveguide, which proves the feasi-

bility of this integration and coupling scheme. In addition to the desired coupling to the SU8 waveguide, there is also light leaked to the packaging glass and coming out at the edge of the glass in the picture. The light output intensities from the waveguide and from the PLED are measured individually, and the coupling efficiency from the PLED to the waveguide is roughly 1%. Because of the high intensity of the PLED, the light propagating in the waveguide is rather strong and can be clearly seen by the eyes.

In order to demonstrate this OEIC device is able to convert electrical signal to optical signals propagating through the waveguide, the PLED is directly modulated by a function generator (HP33120A). A lens is placed in front of the end of the waveguide to collect the light coming out from the waveguide into a detector (New Focus 1801, 125 kHz or New Focus 1601, 30 kHz–1 GHz) which converts the optical signals back into the electrical signals. Before sending the electrical signals into the oscilloscope to monitor the modulation situation, a preamplifier is used to increase the signals. The measurement configuration is also showed in Fig. 1. We study the direct modulation of another separated PLED with structure glass/Au (200 Å)/Super-Yellow (700 Å)/LiF (20 Å)/Ca (350 Å)/Al (1000 Å). This separated PLED with an identical structure is used to simulate the one on the waveguide. Both the separated PLED and the PLED on the waveguide are modulated with 8 V (peak-to-peak) square waves. Figure 3 shows the modulation characteristics of the light coming out from the PLED, the waveguide, and the reference electrical signal of the function generator. When the modulation frequency is low, both light from the PLED and waveguide completely follow the reference signal. When the modulation frequency is higher than 60 kHz, both of them start to show some transient behaviors as shown in Fig. 3(a). As the frequency is higher than 100 kHz, the optical signals have no steady state any more. Figure 3(b) shows the

modulation characteristics at 200 kHz. Both the light from the PLED and waveguide have the same delay time relative to the reference and the same pulse shape. Therefore, the waveguide and diffuser do not introduce any delay or distortion in light propagation. Thus we demonstrate that electrical signals up to 200 kHz can be easily converted to intense waveguide optical signals on Si substrate. In our structure the only limit for the modulation frequency is the PLED itself. In addition to the wave form distortion, the slow response of the PLED also manifests in the light output delay time relative to the function generator, which is 1.5 $\mu$s at 200 kHz as shown in Fig. 3(b). The reciprocal of 1.5 $\mu$s is 667 kHz, which coincide well with the observed maximal frequency at which the light output still respond clearly to the function generator. Such a delay is due to the slow carrier motion across the PLED caused by low mobility. In order to reach out to the desired 100 MHz GHz modulation speed, extend modulator has to be incorporated to the waveguide.

As seen in Fig. 2, the emission from the waveguide is redshifted from the yellow of the PLED to orange. This redshift may be caused by two probabilities: the wavelength dependence of the diffuser scattering and the waveguide scattering. To identify the main reason, a device without diffuser is made and we found emission from the waveguide is still redshifted. This result suggests that the shift is caused by SU8 waveguide scattering of light with shorter wavelengths. This problem become insignificant when the light source itself is in the red or near-infrared region suitable for communication applications especially for local area networks (LAN). Infrared transition-metal complex like Er[8] can be in principle incorporated into the PLED such that infrared emission comes out due to energy transfer. Even though the direct modulation of the PLED cannot achieve the standard communication frequency level of megahertz for LAN, there are other methods to improve the modulation speed.[12,13] The electroluminescence delay time is mainly due to the transport of the faster carrier, i.e., hole for Super-Yellow, through the emissive polymer layer. Simple estimate shows that the *RC* delay needed to charge the PLED electrodes only contribute a minor part to the observed delay time. The mobility is calculated to be about $10^{-5}$ cm/V s, which is roughly the same as previous reports,[14,15] with minor discrepancy due to differences in levels of oxidation[16] or chain conformation.[17]

In summary, a PLED combined with a SU8 waveguide are fabricated on a Si substrate with all the spin-coating fabrication processes which is very compatible for Si technology. When the PLED is turned on, the light from PLED is coupled into SU8 waveguide by a diffuser scattering. Good direct modulation characteristics is demonstrated up to 200 kHz. The overall power coupling efficiency is about 1%.

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