A proximity sensor that combines a polymer light-emitting diode and a polymer photodiode is presented. The operation wavelength is in the near infrared from 700 to 850 nm. The infrared emission is obtained by adding a color conversion film of polystyrenepolythiophene polymer matrix blended with infrared dye 1,1-diethyl-2,2-dicarbocyanine iodide to a red polymer light-emitting diode. The photodetector relies on the direct charge-transfer excitation generation in a donor-acceptor polymer blend of poly(3-hexylthiophene) and (6,6)-phenyl-C$_{61}$-butyric acid methyl ester. The detection distance is up to 19 cm for objects with various colors and roughness under ambient indoor lighting. © 2008 American Institute of Physics. [DOI: 10.1063/1.2949069]
of the donor around 0.4 eV, the lowest excited state of the PCBM acceptor is larger than the exciton binding energy in the NIR range is more challenging. Because the energy difference is about the same as the NIR emission due to the small absorption of the NIR dye, resulting in an efficient NIR emission. The peak of the NIR emission is of 750 nm. The absorption of the NIR dye, resulting in an efficient NIR emission. The peak of the NIR emission is of 750 nm. The absorption of the NIR dye is 0.4 wt% in PVP. The luminescence-voltage characteristics of the red PLED with and without the color convertor are shown in Fig. 2(b) together with their emission spectra. Even though the color conversion film is as thick as 10 μm the red emission is about the same as the NIR emission due to the small absorption cross section of the conversion film with low concentration of the dye. Nevertheless due to the high luminescence of the red PLED the NIR emission is strong enough for the proximity sensor when the PLED is biased at only 9 V.

Compared to NIR emission the detection of the photons in NIR range is more challenging. Because the energy difference between the electron affinities of the P3HT donor and the PCBM acceptor is larger than the exciton binding energy of the donor around 0.4 eV, the lowest excited state of the donor-acceptor bulk heterojunction blend is expected to be the charge-transfer exciton, which is a bound state of a hole in P3HT and an electron in PCBM. Unlike excitons, which involves only one molecule, the charge-transfer exciton involves two different molecules and the Coulomb interaction depends on the details of the intermolecular geometry. In other words the charge-transfer exciton does not have a definite energy but a broad distribution below the exciton. Since the P3HT exciton energy is 1.9 eV (650 nm), the charge-transfer exciton energy is expected to cover the NIR region. The incident photon to current conversion efficiency (IPCE) is defined as number of electron per photon, of a photodetector made of a blend with thickness of 200 nm under reverse bias of 5 V is shown in Fig. 3. The photocurrent spectrum basically follows the absorption spectrum of P3HT and the device responds only to the visible photons with the residual response at the NIR barely seen. As the blend film thickness is increased to 14 μm the NIR photocurrent response due to the charge-transfer exciton dominates the IPCE spectrum, as shown in Fig. 3. The IPCE at various bias voltages are shown. At reverse bias of 200 V it reaches as high as 58% at 750 nm and remains 8% at 10 V in the 14 μm devices. The reverse bias of 10 V is used in the proximity sensor measurement below. The photons in the visible range are all absorbed near PEDOT electrode because the film is too thick for the photons to penetrate through the bulk. Recombination takes places before the photocarriers are collected by the opposite Ca/Al electrode. So despite of the strong absorption there is no photocurrent in the visible range. On the other hand, the
Infrared photons have weaker absorption coefficient and are able to penetrate into the bulk to generate a uniform distribution of photocarriers for 14 nm films.

The PLED with NIR color convertor and the polymer photodetector are placed side by side in the same plane to form the proximity sensor. The active area is 0.25 cm² for both PLED and photodetector. In principle they can be integrated on the same substrate not only as a single pixel but also as an array. For simplicity they are made on separate glass substrates in this work. An object is placed in the normal direction with changing distances. In order to reduce the contribution of the ambient indoor lighting to the photodetector a P3HT film is placed in front of the photodetector to remove photons with wavelength smaller than 650 nm. Before the PLED is turned on there are two sources of background off current in the photodetector. One is the dark current the other is the photocurrent due to the residual infrared light in the indoor surrounding. We measure the NIR proximity sensor in two different modes, dc mode and ac mode. In the dc mode the photocurrent is obtained by subtracting the off current from the on current when the NIR PLED is turned on. The dark current is independent of the object while the ambient infrared current depends on the distance of the object since it either blocks or reflects the ambient lights.

The total off current as a function of the distance is shown in Fig. 4. The response of the detection as function of the distance of white paper (solid square), red paper (empty square), green paper (solid circle), blue paper (empty circle), black paper (solid triangle), aluminum foil (empty triangle), and styrofoam (solid star) measured in (a) dc mode and in (b) ac mode. The total off current is composed of the device dark current and photocurrent induced from surrounding NIR is also shown on the panel (empty star). The inset shows the schematic working principle of the polymer proximity sensor.

Even though the detection is achieved, the sensitivity of the dc mode of detection is limited by the large background off current, which exists before the PLED is turned on. In order to remove the background we perform on ac mode of detection where the PLED is modulated by a square wave of 10 Hz and a lock-in amplifier is used to read the modulated signal. The interferences from the ambient light and the dark current are removed. The results of ac mode measurement are shown in Fig. 4(b). Here we use a resistor to convert the photocurrent to voltage, which can be measured by the lock-in amplifier. As expected the background signal before the PLED is turned on is now much smaller than the desired signal with the PLED switched on. There is now no need to subtract a large background as in the dc mode. The maximum detection distances are 15 cm for styrofoam and 15 cm for aluminum foil. The sensitivity for the detection of skin and clothes is about the same as white paper.
mum detection distances are 19 cm for white and red papers, 17 cm for green and blue, and 9 cm for black. In the comparison of different surfaces the maximum detection distances are 15 cm for styrofoam and 19 cm for aluminum foil. Although the detection distance is affected by the color and surface roughness of the object, the detection distances for all the materials are larger than 9 cm. We expect all other objects in common surroundings of the moving machine to have a higher reflection of NIR light than the black paper and can, hence, be detected beyond 10 cm distance. By the fabrication of arrays of such NIR PLED and photodetector in a flexible substrate as sensitive skin the moving machine will be able to avoid collisions with random objects as it navigates through unstructured environment.

In conclusion we have combined a PLED and a polymer photodiode to make an optical proximity sensor. The operation of the sensor is in NIR range to reduce the influence of the scattered light and the visible light noise. The detection distance depends on the color and roughness of the object surface. The maximum detection distance under normal incidence is almost 20 cm for white paper, styrofoam, and aluminum foil. For all the objects the detection distances are larger than 9 cm, which is enough for the application in skins of robots or machines, which need to move in an unpredictable surrounding.

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