Flexible X-ray detector with high sensitivity using low cost, solution-processed organic photodiodes

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We made and characterized an X-ray detector on a plastic substrate that is capable of medical-grade performance. As an indirect flat panel detector (FPD), it combined a standard scintillator with a novel, solution-processed organic photodetector layer and oxide thin-film transistor (TFT) backplane.

Organic semiconductors are very appealing for light detection applications. They combine effective light absorption from ultraviolet to near-infrared with good photogeneration yield, sensitivity and response time. These materials can be processed from solution over large area, making them specifically attractive for large area imagers such as X-ray detectors for medical applications.

Figure 1A shows the device structure and characteristics of our most recent organic photodetector. A blend of a p-type polymer and n-type small molecule, [6,6]-phenyl C61 butyric acid methyl ester (PCBM), is used as a photoactive layer. After process optimization, we can reliably slotdie coat 280±5 nm films on 15x15 cm substrate area. A photograph of such a film is given in Fig. 1B. Devices show very low dark current of 1-5 pA/mm^2 (Figure 1C) and high sensitivity of 0.2 A/W (Figure 1D) in the green wavelength range (Figure 1E), i.e. nicely compatible with emitted wavelengths of typical X-ray phosphor materials. Detectivities D* (measured in units of Jones, (1 Jones = 1 cmHz$^{1/2}$/W) were calculated based on the measured photocurrent, dark current, and incident light intensity) using $D^* = R/(2qJ_d)^{1/2}$ where q is the absolute value of electron charge (1.6×10^{-19} C) and J_d is the dark current density. The use of eq. 1 implies that the dark current is the major contribution to the noise that limits D*. At -2 V bias, the calculated detectivity is $D^* = 3 \times 10^{13}$ Jones (in the visible range). This is amongst the highest values reported so far for OPDs [1], and meets the requirements [8]. In Fig. 1F, OPD dark current densities with varying temperature are presented showing temperature activated dark currents at working temperatures (from -20 to +80 °C). At -20V the dark current density is ~0.3 pA/mm^2. At the highest temperature, 80C, the dark current density is ~40 pA/mm^2. Such a strong (non-exponential) temperature activation suggests that charge trapping and/or Schottky barriers effectively reduce the dark current in our devices.

The outstanding optical characteristics are retained when these photodiodes are combined with an flexible TFT array (Figure 2A). A matrix of 120 × 160 pixels 126 × 126 µm^2 in size is built on a PEN substrate. A photomicrograph of a single pixel is shown in Figure 2B. The plastic PEN substrate sets an upper temperature limit where acceptable TFTs backplanes must be achieved. a-Si and LTPS transistors typically require process temperatures in the range of 300-450°C. Alternatively, Indium-Gallium-Zinc-Oxide (IGZO) has been demonstrated to give high mobilities (~10-20 cm^2/Vs) at significantly lower process temperature. Figure 2C shows the transfer characteristics of low-temperature (250C) IGZO transistor switches. Please note the low off-currents. The low leakage current is due to the large band gap of IGZO of ~3 eV. Off-currents remain very low, less than 10^{-14} A/μm up to 105°C for a W/L of 60/20 um/um. This aids in improving the sensitivity and robustness of the final array.

Each photodiode is connected to a common bias line and the drain of its associated TFT. The TFTs are controlled by their associated gate lines and when addressed, transfer stored charge onto all the data lines. During each line time (approximately 0.2 ms), a gate line is turned on for approximately 20 μs, allowing sufficient time for the TFTs on that row to transfer their pixel charges to all data lines. The charges are integrated in the associated charge sensitive amplifiers, where they are converted to voltage, digitized and transferred to PC memory. The gate lines are turned on in sequence, requiring approximately 150 ms for an entire frame to be scanned, dependent on A/D conversion resolution.

We first characterize our detector by measuring its optical response at frame rates typically 10 Hz or less. The image in Figure 3A is created by placing an object on top of the array. The image is corrected for the dark background. The visible point and line defects are due to process defects, mostly due to particles. By combining with a scintillator layer on top of the arrays, we tested the detector also with X-ray. Fig. 3B shows the image of a standard X-ray resolution target (thin lead stripes) obtained at 70 kVp averaging 10 frames of 300 ms duration and 100 μGy dose. The image is offset and gain corrected. In Fig. 3C the mean signal of an offset corrected plain image is plotted versus the X-ray dose with a linear fit curve applied to the data points. The lowest dose of 3 μGy/frame is equivalent to a light intensity of only 15 nW/cm^2 taking into account the known scintillator light output and an optical coupling loss of 0.7. From the linear response, an EQE of 25% was calculated (including fill factor already).

Optical and X-ray edge images are shown in Fig. 3C and 3D, resp.: the higher resolution of the optical image is clearly visible as expected with a thick scintillator. From the edge images an oversampled edge spread function and finally the Modulation Transfer Function for the optical as well as for the X-ray measurement is calculated (Fig. 3F). The optical MTF is modeled by a circular aperture function of 96 μm and assuming an optical gap of 40 μm, which can be easily related to the barrier layer on top of the organic diodes. For explaining the X-ray measurement, a usual MTF from thick CsI is convoluted with a 50 μm optical gap, to take into account the protective coatings on top of the OPD as well.

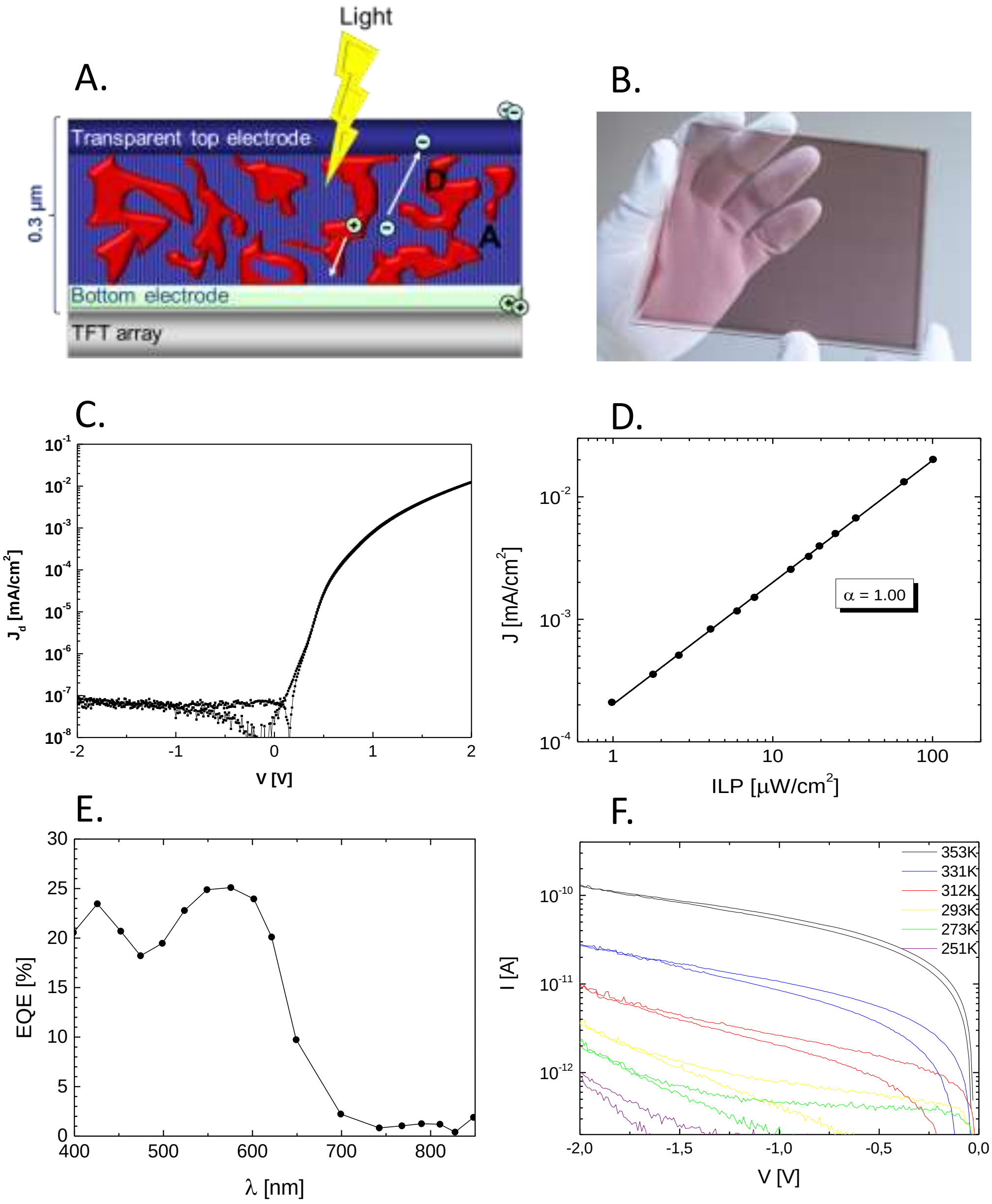

Figure 1. (A) Cross section of the solution processed bulk heterojunction photodetector on foil with p-type polymer donor (D) and small molecule n-type acceptor (A). (B) Photograph of a slot die coated film on a 15x15 cm glass substrate. (C) Current-voltage response under dark conditions. (D) Current density as a function of incident light power. (E) External quantum efficiency as a function of wavelength. (F) Reverse current of a 2x2 mm^2 OPD as a function of temperature (in K), measured in the dark.

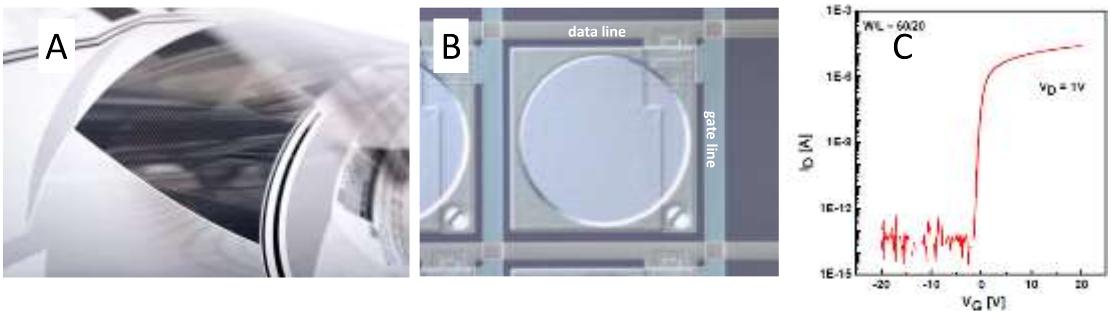

Figure 2. (A) Photograph of a flexible IGZO backplane. (B) Micrograph of a pixel. (C) Current-voltage characteristics of IGZO TFT on foil.

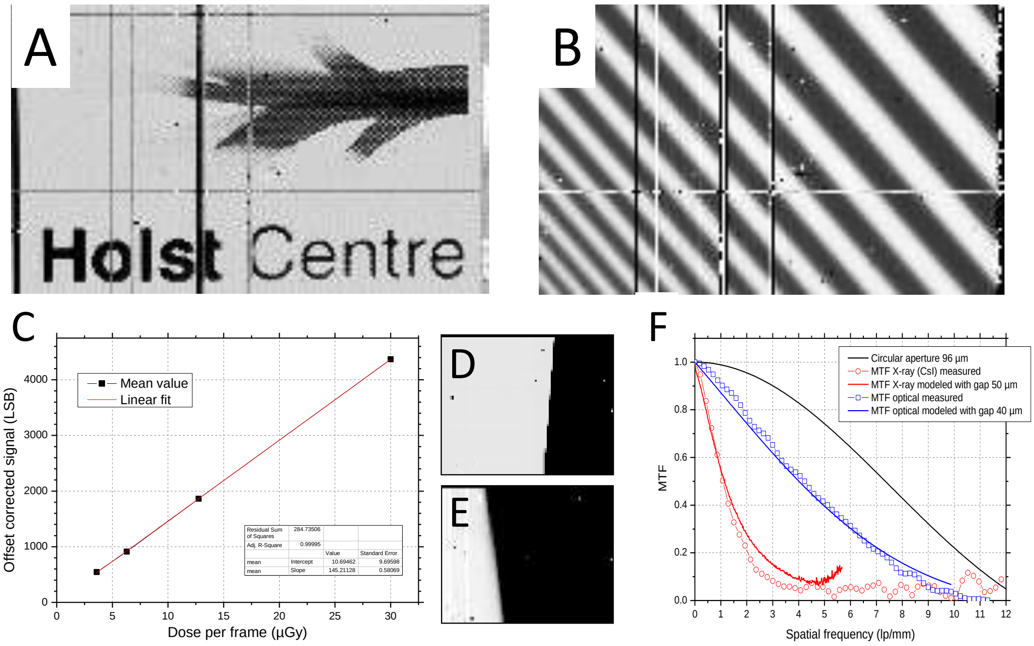

Figure 3. Optical (A) and X-ray image (B) of our detector on foil. Linear response to X-ray dose (C). Zoomed in edge pictures of optical (D) and X-ray € images, used to calculate MTF (F).