Ultraviolet Photodetectors and their Readout Realization for Future Active-Matrix Sensing

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ABSTRACT

Different types of ultraviolet photodetectors and their suitability for active-matrix sensing are discussed. Phototransistors are compared to photoconductors in terms of sensitivity, efficiency and response time. The photosensor readout is implemented by a transimpedance amplifier consisting of a-IGZO TFTs. Measurements with a 64-pixel array are shown to illustrate the applications.

1 Introduction

The detection of ultraviolet light has applications in fire monitoring, space communication or biomedicine [1]. In general, three different sensor types are possible using thin-film technology. These are photodiodes, photoconductors and phototransistors. Photodiodes typically have a vertical structure featuring either a p-n junction or a Schottky junction. In contrast photoconductors have a lateral structure and are based on ohmic junctions. Both are two-terminal devices. Phototransistors are single-gate transistors with three terminals. In this work phototransistors are compared to photoconductors in a metal-semiconductor metal structure. For both sensor structures amorphous indium gallium zinc oxide (a-IGZO) is used as semiconductor material. The performance of the created sensors is characterized by their sensitivity, efficiency and response time. Moreover, the ways the different sensor structures can be integrated in the sensor readout are discussed. In this context results on the realization of an active matrix sensor array are shown. In a first step towards active matrix sensing phototransistors and switching transistors have to be produced on the same substrate. Compatible manufacturing processes are a prerequisite for this.

An on glass-transimpedance amplifier consisting of a 19 dual gate thin-film transistor operational amplifier and a switched capacitor as feedback resistance can be used to convert the sensor signal to a voltage. Pixels can be addressed and read out by the help of multiplexers or shift registers. In addition, first spatially resolved measurements with a 64-pixel passive-matrix array illustrate applications of ultraviolet photosensor arrays.

2 Photosensor layer structures

In figure 1 the layer structures of a phototransistor and a photoconductor are shown. As phototransistors single gate thin-film transistors in a bottom gate coplanar architecture are used. The gate metal is realized by a 70 nm thick MoTa layer. The semiconductor channel (40 nm a-IGZO) is isolated from the gate metal by a double layer of silicon nitride and silicon oxide (175 nm/50 nm). The drain and the source electrode consist of a double layer MoTa/ITO (70 nm/50 nm). The last layer is a passivation made of 130 nm SiOx.

Figure 1: Layer structure: A) Single-gate phototransistor with a channel geometry of \( w = 10 \mu m \times l = 10 \mu m \times h = 40 \) nm. B) MSM-structure photosensor with an active layer geometry of \( w = 100 \mu m \times l = 10 \mu m \times h = 140 \) nm.

3 Photosensor characteristics

The ability to convert an optical input signal into an electrical output signal can be determined by comparing \( I-V \) relations with and without light exposure (LED: light intensity \( I_{light} = 4.5 \) mW/cm² and wavelength \( \lambda = 385 \) nm). For gate-source voltages \( V_{GS} \) smaller than the threshold voltage \( V_{TH} = -2.04 \) V the measured phototransistors show dark currents smaller than 1 pA. For \( V_{GS} > V_{TH} \) the drain current \( I_D \) increases due to the formation of a conductive channel. Under light exposure the threshold voltage \( V_{TH} \) is decreased and thus for negative gate-source voltages the current is strongly increased. The reason for this behavior is the creation of electron-hole pairs and the related increase of the charge-carrier concentration due to the light exposure. To use a single-gate transistor as a photosensor \( V_{GS} \) has to be lower than \( V_{TH} \). The drain-source voltage \( V_{DS} \) has to be larger than \( V_{GS} - V_{TH} \). The best operation value for \( V_{GS} \) is slightly smaller than the threshold voltage \( V_{TH} \), because at this point the difference between \( I_D \) with and without light is maximal. For voltages between the electrodes \( V \) ranging from -20 V to 20 V the MSM-structure sensors have dark currents \( I \) lower than 0.27 nA. If the device is exposed to ultraviolet light \( (I_{light} = 4.5 \) mW/cm²) the current increases by orders of magnitude. The largest current difference between with and without light exposure is determined for the maximal measured voltage of 20 V.
The sensors performances are compared in sensitivity (lowest detectable signal), responsivity (conversion efficiency from optical input into electrical output) and response time (reaction speed). The determined values are displayed in Table 1. The sensitivity is given by the noise-equivalent power value, which is the light power resulting in a signal-to-noise ratio of one at a 1 Hz output bandwidth. During the measurement $V_{DS}$ is set to 30 V and $V_{GS}$ to -10 V. The voltage $V_{DS}$ between the electrodes of the photodetector is 30 V. The phototransistor has in comparison to the photoconductor a lower NEP value and therefore a better sensitivity. This can be explained by the lower dark current, caused by the electric field which repels electrons. The responsivity is defined as $R = (I_{\text{light}} - I_{\text{dark}})/P$, where $I_{\text{light}}$ is the current under light exposure, $I_{\text{dark}}$ is the current without light and $P$ is the light power reaching the active area of the sensor. Under the same circumstances (temperature, light power, wavelength and voltage) phototransistors show higher responsivity values than photoconductors. How fast a sensor can respond to a change in the input signal intensity is given by the response time. The response time $t_{\text{res}}$(up/down) is defined as the rise time from 10% to 90% and the fall time from 90% to 10% of the output signal change respectively. In Figure 3 the time dependent responses of the two sensor structures for switching optical input signals are shown. For photoconductors using gold electrodes response times in the low millisecond range are measured. In comparison to this the response time of the phototransistors is really long. Values of several seconds or even minutes are detected. A microsecond long positive gate/source voltage pulse can reset the drain current $I_D$ to the initial value. During the gate pulse the drain current is strongly increased. The reset takes only hundreds of microseconds. Because of this the response time can be adjusted by the time delay between the gate pulses. Lower delay times lead to improved response times but also to decreasing responsivity values. So, there is a trade-off between reaction time and conversion efficiency. Moreover, the phototransistor is not functional during the gate pulse, therefore phototransistor have dead times. To minimize these the duration of the gate pulse should be selected as short as possible. Therefore, the duration of the measuring period ($V_{GS} < V_{TH}$) should be larger than the reset pulse time ($V_{GS} > V_{TH}$). The measuring point should be taken at the end of the measuring period shortly before the result pulse to achieve the best possible sensitivity for a certain gate pulse frequency. In the shown measurement the measuring points and thus the final photosensor signal is given by the green data points. In general, the slow response time of photosensors using a-IGZO thin films can be explained by the persistent photoconductivity induced by trapped electrons and metastable donors [3].
thin-film transistor operational amplifier and a switched capacitor circuit as feedback resistance. The operational amplifier has an open-loop gain $V_0$ of 32.51 dB and a unity-gain frequency $f_{ug}$ of 3.4 kHz. A switched capacitor circuit consisting of 4 transistors and one capacitor has in the temporal mean a resistance of $R_{sc} = 1/(4 \cdot C \cdot f_{sc})$. At a switching frequency $f_{sc}$ of 2.5 kHz the transimpedance amplifier has a theoretical conversion gain of $G = R_{sc}(1 + 1/V_0) = -156.88 \, \text{dBΩ}$. For frequencies lower than 1 kHz the measured data (-155.54 dB) are close to the theoretical value. The phase difference between input current and output voltage is -172.8°. The theoretical expected value is -180°. For frequencies larger than 1 kHz the absolute conversion gain is decreasing and the phase difference is increasing with increasing frequency $f$. The bandwidth of the TIA is thus 1 kHz. The sensitivity can be extracted from figure 4 B). The output voltage depends linearly on the input current. The high conversion gain translates from currents in the low nA-regime to voltages in the V-regime. A low nA current or even a few hundred pA can be determined as the detection limit. The detection limit has to be considered if the on-glass TIA is used as the readout of a photosensor. The detection limit should be lower than the dark current of the sensor if not the sensitivity of the sensing device is decreased.

To improve the readout characteristics the open-loop gain and the bandwidth of the operational amplifier should be improved. The bandwidth can be increased by eliminating parasitic capacities caused by overlaps between drain/source and gate of the transistors. A solution would be the use of a self-aligned transistor process, because such transistor structures do not have overlaps between drain/source and gate. One way to improve the open-loop gain is to use depletion loads instead of enhancement loads in the operational amplifier circuit. This requires the realization of enhancement and depletion type transistors on the same substrate. This is more complex, time- and cost intensive and error-prone. To produce readout and sensor on the same substrate the manufacturing processes have to be compatible. In the case of photoconductors in an MSM-structure the photosensor is produced on top of the transistor layer stack. Therefore, the total layer stack is consisting of 11 layers structured in 9 lithography steps. For phototransistors the sensor and readout can be manufactured simultaneously. Therefore only 8 layers structured in 6 lithography steps are needed. This leads to lower production time and costs.

### 5 Sensor array

To show application possibilities of sensor arrays first measurements with a passive-matrix array with external control and readout circuit are demonstrated. The sensor array consists of 64-pixels arranged in 8 rows and 8 columns. In both directions the distance between two pixels is 0.5 mm. The already introduced photoconductor structure is used as sensing device. A microscopy image of a part of the sensor array is shown in figure 5. The column lines are realized in aluminum which is separated by a SiOx layer from the chromium/gold row lines. VIAs at the needed positions connect the gold electrodes with the column lines.

![Microscopy image of a passive-matrix array. The distance between two sensors in both directions is 500 μm.](image)

The control and readout circuit of the sensor array consists of two multiplexers, a transimpedance amplifier (TIA), an inverting amplifier and one Arduino. The electronic circuit is realized on a PCB substrate and is connected to the on-glass sensor array with a flex PCB cable. The outputs of the first multiplexer are connected to the row lines of the sensor array. With this a voltage of 7 V is applied to the selected row. The other rows are set to 0 V. The inputs of the second multiplexer are attached to the column lines of the array. This allows a column-selective readout by the transimpedance amplifier. Using both multiplexers a single sensor of the array can be measured. The multiplexers are controlled by the Arduino. Moreover, one of the analog inputs of the Arduino reads the by the TIA measured data and converts it to digital signal. A graphical interface which displays the sensor array is programmed in the Python framework Kivy. In figure 5 the measurement of the beam size of an ultraviolet laser at 226 nm is shown. The laser beam is irradiated perpendicular to the surface of the sensor array. The pixel with the highest current increase, which is equal to the highest recorded light power is determined as the center of the laser beam. The intensity profile of a gaussian beam is described by $I(r) = I_{max} \cdot \exp(-2 \cdot (r^2 - b^2)/w^2)$ with the maximal intensity $I_{max}$, the spatial coordinate vector $r = (x, y)$, the displacement vector $b$ and the beam waist $(1/e^2) w = (w_x, w_y)$. From the fitted beam waist parameters the full width at half maximum values can calculated by $FWHM_{x/y} = 2 \cdot w_{x/y} \cdot \sqrt{\ln(2)} \cdot \sqrt{2}$. 

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**Figure 4**: A) Absolute $I$-$V$ conversion gain $G$ and phase $P$ response of the transimpedance amplifier depending on the frequency $f$. B) Output voltage $V$ of the transimpedance amplifier depending on the input current $I$.

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**Figure 5**: Microscopy image of a passive-matrix array. The distance between two sensors in both directions is 500 μm.
The most present drawback of the passive-matrix realization is crosstalk between neighboring sensors. Another problem is that the individual sensors show slightly different responsivities under same circumstances. This is caused by manufacturing imperfections. A calibration of the sensor array can help to minimize this effect.

6 Active-matrix sensing

To change to an active-matrix sensor array every pixel consists of a sensor and a switching transistor now. As switching transistor, a dual-gate TFT is used because the top-gate shields the semiconductor channel from the light and prevents the creation of charge carriers. Because of the superior quality factors phototransistors should be used as photo sensing devices. An illustration and a microscopy image of such a sensing pixel are shown in figures 7 and 8. The drain-source voltages of all phototransistors are set to a constant value. This means in contrast to the passive-matrix array the row lines are not connected to the photosensors. Instead the row lines are attached to the gates of the switching transistors. Therefore, rows can be turned off. This reduces crosstalk, because of the low cut-off current of a-IGZO TFTs. A shift register or a multiplexer can be used to scan through the rows. Additional connections to the gates of the phototransistors are needed to send the control signal. The transimpedance amplifier is realized on the glass substrate. This enables the possibility to give every column or even every sensor an individual TIA. The benefit is that the signal path from sensor to corresponding TIA is only a few micrometers. Additionally, high voltage signals instead of low current signals have to be sent through a multiplexer. Therefore, the signal-to-noise ratio should be improved. The overall goal is to realize the control/readout circuit also on the glass substrate based on a-IGZO semiconductor technology.

7 Conclusions

This study presents a comparison between phototransistors and photoconductors using a-IGZO thin films for the detection of ultraviolet light. Phototransistors show better responsivity and sensitivity than photoconductors. Moreover, response times lower than 1 ms can be achieved by sending positive gate-source voltage pulses. Additionally, phototransistors can be manufactured simultaneously to switching transistors in an active-matrix sensor array, which reduces the number of production steps and costs. An on-glass transimpedance amplifier consisting of dual-gate a-IGZO TFTs can convert the sensor current into a voltage. A 64-pixel passive-matrix array is used to measure the beam size of an ultraviolet laser at 226 nm. Plans and first results towards the implementation of an active-matrix sensor array are discussed. This involves phototransistors as sensing devices and the creation of the control and readout through thin-film transistors using a-IGZO.

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