INFLUENCE OF TRANSPARENT ELECTRODES ON
IMAGE SENSOR PERFORMANCE

K. KEMPTER, H. WIECZOREK AND M. HOHEISEL
Siemens AG, Research Laboratories, D-8000 München 83, Fed. Rep. of Germany

ABSTRACT

The short response times required for image sensors demand blocking contacts at the sensor cell. It was found that the junctions between transparent electrodes (ITO or a thin palladium film) and the metallic back electrode with a-Si:H form blocking contacts yielding photocurrent decay times of the order of some microseconds. The two different time regimes observed for the decay are interpreted as being limited by the drift and the release of holes respectively.

I. INTRODUCTION

Image sensors having the size of an A-4 document depend on the availability of large-area photoconductors. These materials have been common for more than 20 years as photoreceptors in the field of electrophotography. However, image sensors require, as an additional feature, a response time shorter than 100 μs, in contrast to the 100 ms required in electrophotography.

This speed requirement cannot be met by a simple photoconductor; rather, it demands a photodiode with blocking contacts. Furthermore the photoactive material must show a high carrier mobility and a minimum of dispersive transport. Amorphous hydrogenated silicon (a-Si:H) is considered a highly suitable material for such image sensors. To obtain the diode behaviour with carrier depletion necessary for high speed response some of the sensors discussed in the literature employ a p-i-n structure /1/ or additional blocking layers (mostly Si_3N_4)/2/. Others relay on the blocking effect of the contacts /3, 4/.

This paper presents some results which were obtained in an attempt to use sandwich cells consisting merely of a metallic back electrode, undoped a-Si:H and a transparent top electrode. The blocking effect of the contacts stems from the junctions between a-Si:H and the electrodes. These junctions act as a Schottky barrier or as a heterojunction. The results were selected in accordance with their relevance to image sensor performance with special emphasis on the time response of the sensor cell. Measurements of the photocurrent decay relevant to image sensor performance differ in three aspects from the usual decay investigations reported in the literature /5/. First: the starting point of the decay is the steady-state photocurrent, because the time period between illumination changes of an image sensor is in the range of milliseconds. Therefore, the current decay figures the transport processes during the transition from one equilibrium distribution of the carriers to another. Second: considering the large dynamic range of a sensor, the current decay must be traced down to within a few percent of the initial photocurrent value. This means that the slow tail of the decay is of essential importance. Third: the sensor has a sandwich geometry rather than the gap configuration of the electrodes usual for carrier life-time measurements.

II. EXPERIMENTAL METHODS

The samples used were sandwiched between a metallic back electrode and a transparent top electrode; see FIG. 1.
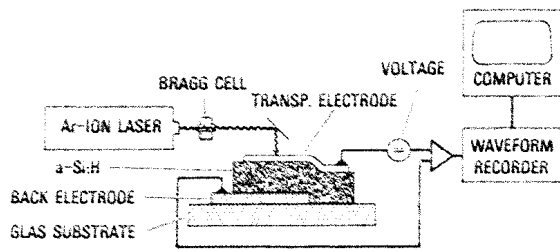
The back electrode consisted of a thin film of a low work-function metal, mostly titanium. The 1 μm thick undoped a-Si:H film was deposited by RF decomposition of pure silane in a capacitively coupled plasma reactor. The deposition parameters were optimized by minimizing the subgap optical absorption, measured by the Constant Photocurrent Method (CPM) /6/. The absorption value α of a typical a-Si:H samples ($T_s = 220°$ C) at hv = 1 eV was in the range of 0.1 cm^{-1}. A sample particularly rich in defects was deposited at $T_s = 150°$ C, yielding an α (1 eV) 0f 1 cm^{-1}. The transparent top electrode was either a semitransparent layer of Pd (10 nm thick) or a 150 nm thick ITO film. All electrodes were evaporated by an electron gun. The patterning of the top electrode was performed either by photolithography in a lift-off process (electrode area 0.2 cm^2) or by a shadow mask during evaporation (electrode area 1.1 cm^2). Patterning by evaporation through a mask avoids contact between the a-Si:H surface and the developer solution containing sodium ions. Sodium penetrating into the a-Si:H may act as a donator. In order to investigate the influence of the oxide layer, the surface of the a-Si:H film was etched with hydrofluoric acid to remove the oxide, or the oxide thickness was increased by an oxygen plasma.

The photocurrent decay was measured after 5 s illumination period with the light of an argon-ion laser (λ = 514 nm) of usually 7.10^{14} photons/cm^{2}s. The laser beam was switched off by a Bragg cell whose fall time was 50 ns. The light-to-dark ratio was 1000:1. The photocurrent was fed to a low-impedance operational preamplifier, which was connected to an HP 5180 waveform recorder. The dynamic range of the measuring circuit was 200:1 down to the dc level. The subsequent analysis was performed with an HP 9836 computer. The shortest decay times measured were a few microseconds. The varying capacitance of the sample under varying bias caused a small influence only to the fastest part of the measured decay because of the low impedance of the amplifier. The dark current was measured before and after every experiment and subtracted to yield the photocurrent.
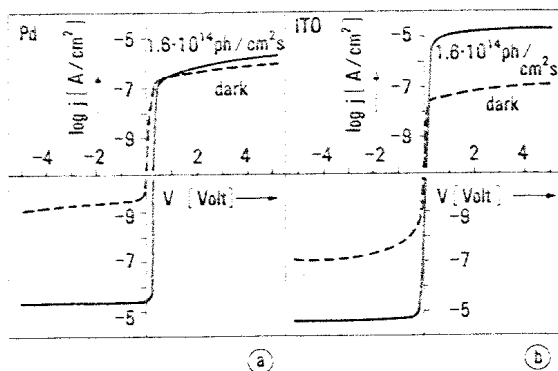

FIG. 1   Experimental system and electrode arrangement in the sample.

FIG.2   Dark and photocurrent as a function of the voltage applied to the top electrode . The value given is the photon flux incident onto the top electrode.

a) Semitransparent palladium as top electrode

b) ITO as top electrode.

III.   EXPERIMENTAL RESULTS

The current - voltage characteristics yield general information on the nature of the contacts. Typical results both for dark and photocurrent are shown in FIG. 2. The voltage polarity given applies in each case to the (illuminated) top electrode. The observed characteristics represent the behaviour of a back-to-back diode with current saturation for both polarities. In the case of the negative-biased top electrode, carrier blocking seems to be more effective, because the (reversed) dark- and photocurrent displays a better saturation. This saturation is more pronounced with a palladium than with an ITO top electrode. The open-circuit voltage of the illuminated sandwich was 0.2 V and 0.1 V with Pd and ITO electrodes, respectively. The smaller photocurrent of the Pd-covered sample is due to the stronger light absorption

of the palladium in comparison with ITO.

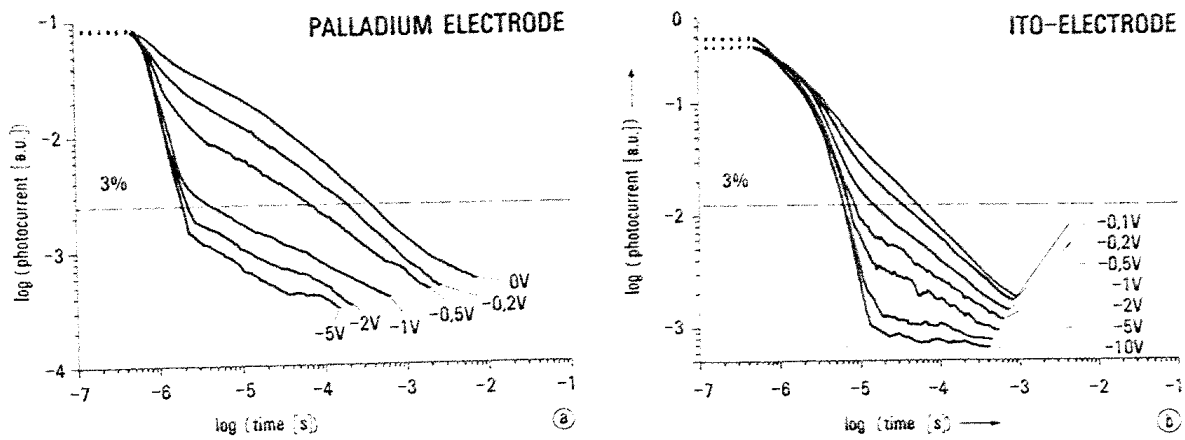Two typical examples of measured photocurrent decay curves are displayed in FIG. 3.

FIG. 3 Photocurrent decay vs. time for various negative voltages. The incident photon flux was $7 \cdot 10^{14}$ photons/cm^2 s.

a) Semitransparent palladium as top electrode

b) ITO as top electrode.

Most of the measured current decays show two parts: a steep drop in the beginning, followed by a slow tail. The steep drop becomes more pronounced as the bias voltage increases. For the following, the decay time will be defined as the time period from the illumination cutoff to the point where the current has dropped to 3 percent of the initial steady-state value.

The results for the 3-percent decay time obtained for different samples are summarized in FIG. 4 as a function of the bias voltage. Most of the samples show a tremendous variation of the decay time extending up to six orders of magnitude. On both sides of the narrow peak near zero bias two broad minima extend in both voltage directions. The shortest decay times were found at moderate negative bias. The absolute value of these decay time minima in the microsecond region may be affected by the measuring circuit. Thus the faster response of the Pd contact (2 µs) seems to result from the smaller resistivity of this electrode in comparison to the ITO electrode.

The increase of the decay time at higher negative bias occurred only with those samples which showed a steep increase of the current at high bias (breakdown of blocking).
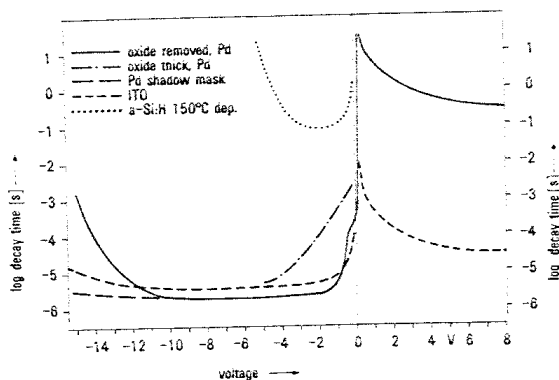

FIG. 4 Decay time for a current drop to 3 percent of the initial value as a function of the applied bias voltage measured on samples with different top electrodes and deposition temperatures of the a-Si:H.

At positive bias, the decay times are generally much longer than at negative bias. Furthermore a great difference between ITO and Pd electrodes was found in this voltage regime.

The influence of the interface can also be seen from the voltage dependence of the sample with the thick oxide interlayer (produced by plasma treatment). A larger negative voltage is necessary to reach the minimum decay time with this sample. The different surface treatments of the interface affected predominantly the reproducibility of the blocking effect of the contacts. Evaporation of the top electrode through a shadow mask renders possible higher negative voltages than photolithographic patterning.
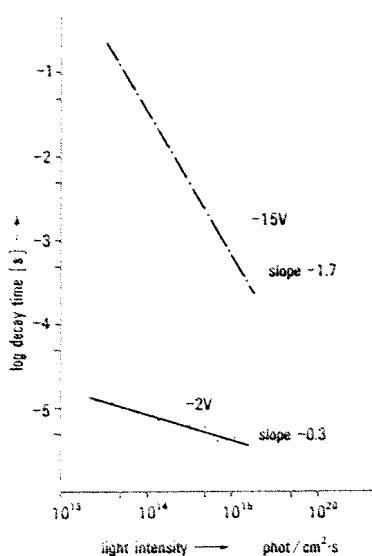
FIG. 5 Decay time for a current drop to 3 percent of initial value as a function of the light intensity, measured with a Pd top electrode,
  a) at a voltage of -2V,
  b) at a voltage of -15 V (breakdown of blocking).

The sensor consisting of a-Si:H deposited at 150° C shows the strong influence of the bulk material. The minimum decay time is increased by four orders of magnitude.

The dependence of the decay time on the preceding light intensity is displayed in FIG. 5.

For a moderate negative bias, a small decrease of decay time was obtained as the light intensity increased. This dependence on light intensity was found to be much higher at elevated bias voltages, i. e. in the range where the contacts are no longer blocking.

IV. DISCUSSION

There is a great deal of complexity in a complete description of the photocurrent because many different effects may coincide, for instance trapping, recombination, nonuniform carrier distribution, carrier injection, space charge and field distortions /7/. The following discussion attempts to give a very rough estimate of the prevailing physical processes which may be responsible for the observed behaviour.

The I-V characteristics shown in FIG. 2 permit the conclusion that the photocurrent is of the primary type at least with moderate negative bias, in accordance with the assumption of others /8/. In this case electrons and holes are prevented from entering the photoconductor at the electrodes. We assume that the limitation of the photocurrent decay is primarily effected by the holes, because their drift mobility is smaller by two orders of magnitude than the mobility of the electrons /9/. The influence of the electrons on the decay grows as the penetration depth of the light below the negative-biased electrode decreases.

During buildup of the steady-state photocurrent, most of the excess photogenerated holes will be distributed to localized trap states and a few to extended states. After the illumination is terminated, the photocurrent decay reflects the drift of the excess holes to the negative-biased electrode. This current may be limited by the field-dependent drift time of the holes or by the release time of the holes from the traps. Right at the beginning of the decay when the shallow traps (nearest to the valence band) are emptied, the release time is very short and the current is limited by the drift. The drift time of the holes is estimated at one microsecond, assuming a hole mobility of 10^{-3} cm^2/V.s /9/, an internal field of 10^4 V/cm, and a drift length equivalent to the light penetration depth of 0.14 μm. /10/.

During decay, the emptying of the traps proceeds to ever lower energetic states

(more distant from the valence band) so that a point will be reached where the release time exceeds the drift time of the holes; from this point onward the decay will be release-limited. The constant slope of the slow tail is ascribed to the release of holes from a continuous distribution of trap states.

The transition from the initial steep current drop (drift-limited) to the slow tail occurs after about 5 µs. This yields a value of 0.45 eV for the energetic depth of the traps at which release limitation begins (escape frequency was assumed to be 10^{13} s^{-1}).

The pronounced increase of the decay time near zero bias is explained as a consequence of the field drop which increases the drift time of the holes.

The increase of the decay time observed with some samples at high negative bias must be correlated with the injection of electrons from the transparent electrode. Thus, with an additional secondary photocurrent flowing, the long recombination lifetime of the electrons determines the decay time.

For positive bias, the generally longer decay times are explained by the greater drift length of the holes from the illuminated electrode to the back electrode. In this case, the pronounced field dependence supports the model of the transit time limitation. The rather long time scale of this transit can be explained by the dispersive nature of the hole transport /11/. No consistent explanation can be offered so far for the different decay times associated with palladium and ITO electrodes.

To explain the observed decrease of the decay time with light intensity, we shall first consider the release-limited case at moderate negative bias. Increasing light intensity shifts the quasi-Fermi level of the holes closer to the valence band edge. Therefore an increasing part of the trapped holes profit by a shorter release time. Hence the photocurrent drops in a shorter time. The observed slope of the intensity dependence should be correlated with the slope of the relevant trap state density vs. energy.

The much steeper intensity dependence of the decay at high reverse bias (secondary photocurrent) must be due to a variation of the recombination lifetime of the electrons. A decrease of electron lifetime with increasing density of excess carriers has already been found by Snell, Spear and LeComber /12/.

Except for this last case, carrier recombination was not considered, the reason being the generally primary nature of the photocurrent with both polarities of the bias as a consequence of the blocking contacts. The strongly absorbed light is an additional factor making for a marked nonuniformity of the electron and hole distribution across the a-Si:H /7/. As a consequence, recombination is suppressed in most parts of the sample. This is supported by the almost linear dependence between photocurrent and light intensity observed in these samples.

V. SUMMARY

It could be shown that image sensor cells with a very fast response (2 µs) may be realized using suitable electrodes as blocking contacts in conjunction with optimized a-Si:H bulk material.

Interface and surface treatments are of importance to the blocking effect of the electrode (and its reproducibility), which is the basic requirement for the short response time.

The pronounced dependence of the observed photocurrent decay on the bias voltage can be qualitatively explained by a model which is based on drift- or release-limited hole motion.

REFERENCES

1 H. Yamamoto, T. Baji, H. Matsumaru, Y. Tanaka, K. Seki, T. T. Tanaka,
   A. Sasano and T. Tsukada, Ext. Abstr. of 15th Conference on Solid State Devices
   and Materials, Tokyo 1983, pp. 205 – 208

2 S. Kaneko, F. Okumura, H. Uchida, M. Kanamori, M. Sakamoto, T. Itano,
   U. Kajiwara and T. Saito,   J. Non-Cryst. Sol. 59 & 60 (1983) 1227

3 T. Hamano, H. Ito, T. Nakamura, T. Ozawa, M. Fuse and M. Takenouchi,
   Jap. J. Appl. Phys. 21 (1982) Suppl. 21-1, pp. 245

4 K. Suzuki, Y. Suda, S. Takayama, T. Nakai, K. Mori, O. Takikawa and T. Saito,
   IMC Tokyo 1984 Proceedings

5 N. Matsumoto et al., Jap. J. Appl. Phys. 20 (1981) Suppl. 20-2 pp. 179.
   J. M. Hvam and M. H. Brodsky, Phys. Rev. Lett. 46 (1981) 371.
   T. Kagawa et al., Phys. Rev. B 26 (1982) 4714. A. A. Andreev et al. Solid State
   Commun. 52 (1984) 589. W. B. Jackson et al. Solid State Commun. 47 (1983) 435.

6 M. Vanecek, J. Kocka, J. Stuchlik and A. Triska, Solid State Commun. 39 (1981)
   1199.

7 R. S. Crandall in Semicond. and Semimet. (Edit. R. K. Willardson, A. C. Boer)
   Vol. 21 B (Edit. J. I. Pankove) Academic Press 1984 pp. 245

8 W. B. Jackson, R. J. Nemanich and N. M. Amer, Phys. Rev. B 27 (1983) 4861.

9 R. A. Street, Appl. Phys. Lett. 41 (1982) 1060.

10 P. J. Zanzucchi, C. R. Wronski and D. E. Carlson, J. Appl. Phys. 48 (1977) 5227

11 T. Tiedje, J. M. Cebulka, D. L. Morel, B. Abeles, Phys. Rev. Lett. 46 (1981) 1425

12 A. J. Snell, W. E. Spear, and P. G. LeComber, Phil. Mag. B 43 (1981) 407.