Suppression of Staebler-Wronski Effect Induced Electrical Crosstalk in a-Si:H-Based Image Sensors

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ABSTRACT

Hydrogenated amorphous silicon photodiodes have been considered for use in array-based image sensors. They promise to significantly reduce the size and cost of CMOS image sensors, while offering the promise of improved pixel sensitivity. However, Staebler-Wronski Effect (SWE) based electrical crosstalk degradation has been a major concern in their acceptance, due to degraded spatial contrast and color fidelity. Since the SWE is a fundamental mechanism of a Si:H, solutions to this issue must look to ways of mitigating the SWE on diode array performance rather than elimination of SWE. In order to study electrical crosstalk, a novel device structure that inhibits light from reaching portions of the a-Si:H/dielectric interface was designed and fabricated to directly measure interpixel leakage currents. Results from these structures indicate that edge leakage can be a significant contributing component to the measured signal. In addition, a CMOS-compatible structure to suppress electrical crosstalk was designed and fabricated. Results from these structures demonstrate suppression of crosstalk up to lateral electric fields of at least 2×10^4 V/cm. Such suppression is adequate for densely packed minimum-size pixel arrays. Aspects of the design and implementation of the structure will also be discussed.

INTRODUCTION

Over the last ten years, there has been increasing interest in the use of a-Si:H in photodiode arrays that are monolithically integrated onto integrated circuits [1-3]. Such integration allows a combination of 1) reduced imaging pixel area, 2) reduced sensor cost, 3) lower photodiode leakage, and 4) improved pixel sensitivity. As pixel-level complexity (hence area) grows, the advantages become more apparent. However, one major issue that has hindered acceptance of these arrays for visible light applications are imaging artifacts induced by the Staebler-Wronski Effect. Exposure of a-Si:H imagers to focused sunlight (~3000 suns) produced dramatic changes in pixel behavior that were reversible upon heating. One of the most troublesome of these artifacts is the increase in interpixel crosstalk upon Staebler-Wronski based degradation. Sensors have been fabricated in which cross talk in non-degraded material is acceptable, however upon severe enough degradation, crosstalk becomes noticeable. While modifications to the a-Si:H including reducing the degree of hydrogenation have a positive effect, no materials based a-Si:H solution has succeeded in completely suppressing crosstalk. This paper describes the effect of an opaque light shielding structure that for the first time successfully suppresses Staebler-Wronski induced crosstalk by preventing localized degradation within the interpixel region.

EXPERIMENTAL

Details of diode fabrication have been presented elsewhere, and are only briefly described here [1, 2, 4]. Diode array fabrication starts with a standard integrated circuit process flow. The photodiode array consists of n-type a-Si:H pixels overlapping a thin metallic pixel contacts with a common intrinsic and p-type a-Si:H layers that form an array of p-i-n junctions, (see Figure 1). Top contact to the array is made by using a transparent conductor layer that connects the top surface of the p-type a-Si:H layer to vias adjacent to the array, (monolithic top contact structure) [2]. Allowing the transparent conductor to be in contact with the edge of the intrinsic layer for the array simplifies sample construction, but puts the transparent conductor in direct contact with the intrinsic layer [1, 5]. This produces a contact junction that injects current into the array, overwhelming any surface state leakage formed by the physical array edge. However, all test structures are bounded by a ring diode that is held at the same bias as the measurement structure itself, so that it removes the injected current.

The test structures measured for this paper came from a general process development vehicle design for this process flow and consists of junction area about 8.84×10^5 μm^2 with 940 μm square on a side. The n-layer electrode was patterned in a series of 4 μm square pixels with a 1 μm space between them, in a 188 x 188 array. The pixels were connected into two interpenetrating arrays that could be biased independently from one another. The i-layer thickness was 5500Å, the 200Å thick p-layer boron atomic concentration was 7.0×10^{19} cm^{-3}, and the 500Å thick n-layer phosphorus concentration was 2.0×10^{20} cm^{-3}, as measured by SIMS. The arrays were covered with a 600Å transparent conductor layer on top of the p-layer. The a-Si:H layers are formed by very high rate PECVD deposition methods (> 20 Å/s), with the resultant films having an intrinsic defect density of $< 4 \times 10^{15}$ cm^{-3} [1].

In order to create the light shield, a thin layer of metal was deposited on top of the transparent conductor, and patterned using a resist-based process. The metal was thick enough to reduce light transmittance by more than 6 orders of magnitude. The pattern was such as to lie directly over the entire interpixel region, though as will be shown, this is not a necessity. Suitable shields can be made to overlap or underlap the interpixel region.
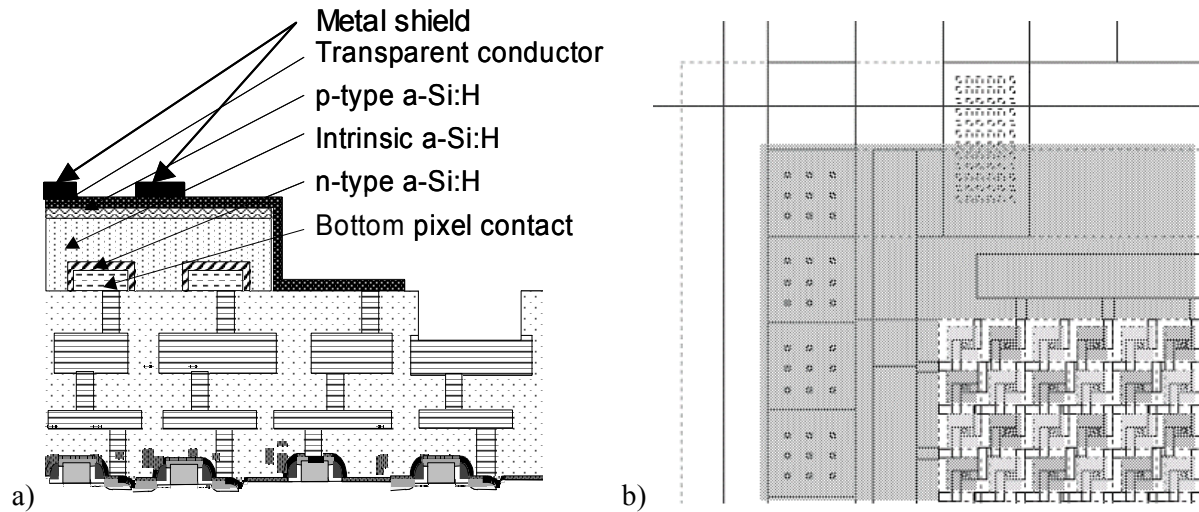

Figure 1: a) Schematic diagram of elevated a-Si:H photodiodes. The metal shield lies over the region between adjacent pixels. It is absent in the control arrays. b) Layout of a corner of the pixel array. The pixels are connected into two interpenetrating checkerboards surrounded by an independently biased guard-ring.

In order to degrade the a-Si:H, the devices were subjected to the ir-filtered light of a 1 kW Xe Arc lamp focused with collimating optics to achieve a light intensity of roughly 3000 suns. Previous experiments showed that the a-Si:H reaches a saturated defect state in 45 seconds. The samples were mounted onto an Aluminum block 6" in diameter, and 4" deep to act as a heat sink, wafer measured temperature changes were less than 5°C from the ambient. For normal direction illumination, (0°), the exposure time was 120 seconds. To illuminate at an angle other than normal, the heat sink was rotated to either 12° or 30° to the light source in both clockwise and counterclockwise direction and were exposed for 120 second at each position. Therefore it is assumed that the films are saturated after each exposure. All measurements were made at room temperature.
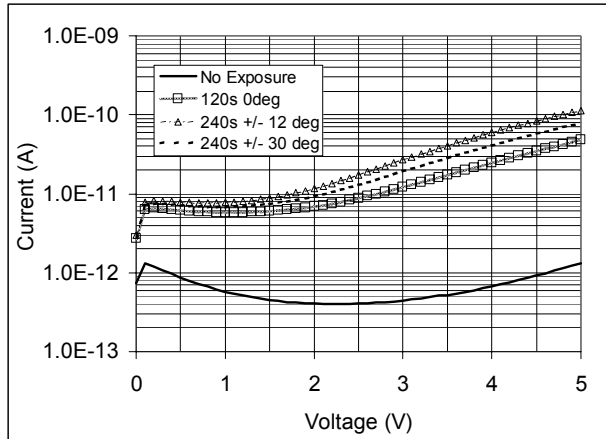
Figure 2: Post-exposure (to a 3000 sun Xe-Arc lamp light source) reverse bias dark current and as a function of exposure duration and angle.

Two types of electrical measurements were made on the devices utilizing an Agilent 4156B. The p-layer was defined as COMMON, the first channel of pixels being swept, V_{pxl}, and the guard ring and second channel of pixels set to a fixed biased $V_{ref} = 2.5$. One was a reverse bias I-V measurement, in which the junction bias was varied from 0 to either 5 or 10V reverse bias in 0.1 V increments. At each measurement point, the measurement was made after a 65 second hold at bias and a long measurement integration time, thus allowing for 40fA sensitivity. The other was a low frequency transient decay measurement made under reverse bias conditions from 0.2 to 4V. In these experiments, the instrument was put into a sampling mode in which data was collected every 0.1s, and the current was monitored from the point at which the diode bias was switched from 0V to the set bias. In all cases, the guard-ring diode that surrounded the structure-under-test was driven with identical voltages but utilizing separate source measurement units, so that there was no current flow between the two devices. All measurements were made in complete darkness and a sample temperature of 21°C.

RESULTS

Figure 2 illustrates the effect of illumination on diode behavior. Both channels were tied together to aggregate the leakage current across the entire array. The effects of exposure time and illumination angle were compared against an unilluminated control measurement for both dark reverse bias. Figure 2 shows that the reverse bias leakage current increases about 30x from about 2 to 5V reverse bias, and at low biases this difference decreases to about 5x. It should be noted that the increase in leakage current is about the same for all degradation conditions, indicating a saturated defect condition. In fact the saturated condition is achieved in about 60 seconds under these illumination conditions.

Figures 3 and 4 show the dark current flowing through one diode as a function of its bias (V_{pxl}) relative to an adjacent diode. The crosstalk bias is the difference in bias between adjacent pixels, ($V_{cxt} = V_{ref} - V_{pxl}$), where is the V_{ref} fixed bias for the second channel. The adjacent diode bias was fixed to a constant 2.5V reverse bias, so that when V_{pxl} is set to 2.5V the bias difference between the two sets of pixels (crosstalk bias, V_{cxt}) is 0V. Starting from the right-hand side of the diagrams, when V_{pxl} is near 2.5V, the measured current through the pixel, I_{pxl}, is relatively constant. However, once the interpixel bias reaches a certain threshold an increase in current is seen (as V_{pxl} decreases). This current becomes roughly exponential after a few volts. Figure 4 shows that when the array has not been exposed to the intense light source that the V_{pxl} for turn on is about 1V, or $V_{cxt} \sim 1.5V$. When an unshielded device is exposed to the light source, post-exposure measurements show that V_{cxt} decrease to about 150 to 400mV. When the array has a metal shield on it and the light shines at normal incidence, V_{cxt} does not change significantly. In addition, when the incident angle increases to +/-12 or +/-30 deg, V_{cxt} does decrease, but only by about 500 mV to 1.0V.
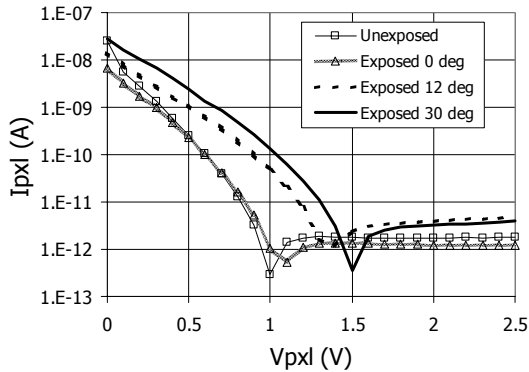
Figure 3: Effect of illumination angle on the change in interpixel leakage as a function of interpixel bias for diode arrays with metal shields on them.
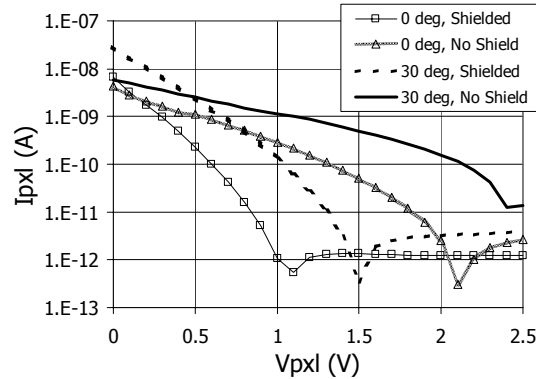

Figure 4: Effect of light shield on the change in interpixel leakage as a function of interpixel bias.

Another interesting point is that in Figure 3, the exponent of the subthreshold current appears to be largely independent of the exposure time when the light shield is in place. Now comparing the subthreshold slope of the unexposed control in Figure 3 with the shielded and unshielded exposures in Figure 4, shows that the subthreshold slope actually decreases when the shield is not in place.

DISCUSSION

There are several features of note in the interpixel curves depicted in Figures 3 and 4 that show there are several simultaneous current sources in the measurement. The flat regions of the curves for low values of V_{cxt} are dominated by junction leakage across the p-i-n junction. This current is higher than for the area junction and is an artifact of increased electric fields due to topography and pixel edge termination [6]. At V_{cxt}, the electric field across the interpixel gap increases to the point that the interpixel current dominates relative to the junction leakage, around 2×10^4 V/cm. It is likely that the interpixel current is similar to subthreshold currents seen in MOS devices given the roughly exponential dependence on bias. Such a-Si:H channel devices rely upon carrier-hopping in localized states in a weak accumulation mode [7-9]. In this case, however, the field applied between the adjacent pixel electrodes is able to induce enough charge in localized states to modulate channel conductance. Upon degradation, the increase in deep-level state population phenomenologically explains the behavior in Figure 4 by depressing the mean state energy, making the interpixel region less responsive to electric field.

The increase in leakage current could be due to changes induced in the doped layers of the junction. Lowering of dopant concentrations produces similar increases due to charge injection, while an increase in the deep-level state concentration has been observed to show an increase in junction leakage. Optically induced damage could be creating similar effects by de-passivation of deep-level states, and possible dopant passivation. The additional deep-level states introduced by degradation are predominantly in the upper half of the gap, therefore they shift the Fermi level closer the conduction band relative to undegraded material, making the intrinsic layer more strongly n-doped. This leads to higher conductance of the degraded material.

For each illumination angle when the shield is in place, a fraction of the interpixel volume remains undegraded. The interpixel region can be thought of consisting of two types of a-Si:H, that with a low dangling bond defect density within the center of the region, and higher density a-Si:H towards the edges. Since the shadowed region remains undegraded and has lower carrier concentration, it limits the conductance of the region. It is likely that as long as the undegraded region remains longer than the mean carrier diffusion length, it will continue to inhibit crosstalk.

The decrease in V_{cxt} increases the likelihood of having crosstalk conditions, as more charge from one pixel may be allowed to diffuse across the interpixel region into an adjacent pixel. Whenever operation of

the pixel results in a bias exceeding V_{cxt}, this potential will exist. This situation can occur in the source follower imager pixel architecture, which is the most common design, because pixel operation allows the photocurrent to completely discharge the diode junction. By placing some sort of voltage clamping mechanism within the circuit to prevent the junction from falling below V_{cxt}, interpixel leakage can be prevented. However, if the supply voltage for the pixel is greater than twice V_{cxt}, voltage clamping will not affect image quality.

Optically though, the shield does reduce the effective light collection area for the pixel as it will reflect/absorb light from a previously photoactive region. However, the design presented here and more efficient layouts will minimize the loss, and even this design results in greater quantum efficiency when compared similar sized pixels with crystalline silicon photodiodes. Finally, there are optical techniques available that can recover most of the lost light without transmitting it into the interpixel region that can bring quantum efficiency to more than 90% of an unshielded diode array.

SUMMARY

Hydrogenated amorphous silicon photodiodes were degraded using an intense light source to study changes in interpixel leakage phenomena. It appears that the degradation drives the intrinsic layer to be more n-type through the introduction of a large number of deep-level states, and is manifested by 1) greater interpixel conduction, and 2) a generally lessened voltage response. The use of an optically opaque shield that covers a portion of the region between pixels has been shown to inhibit interpixel crosstalk even after complete degradation by intense light exposure. This was achieved by maximizing the voltage difference between pixels above which interpixel currents dominate. This technique can be successfully applied to source follower pixel designs without loss of image quality as long as V_{cxt} is kept at less than half of the supply voltage. While there is a loss of light collection efficiency, a-Si:H still have greater quantum efficiency than bulk silicon diode pixels of the same size.

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