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Studies of Semitransparent Optoelectronic Position Sensors (ALMY) for High Precision Alignment Monitoring Systems*

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Abstract— Novel semitransparent optoelectronic position sensors ('ALMY sensors') have been developed for high-precision multi-point position and angle measurements of collimated laser beams over a large measurement range. The sensors consist of a thin film of amorphous silicon deposited on a glass substrate between two transparent layers of crossed strip electrodes. They provide a position resolution of on the order of a micrometer over sensitive areas of several square centimeters. A transmittance of 80 – 90% has been achieved for 780 nm laser light produced by diode lasers. We report about recent optimizations of the sensor performance and tests of the long-term stability under laser illumination and of the radiation tolerance at high neutron doses. As expected, the radiation hardness of the amorphous silicon sensors exceeds the one of crystalline silicon devices. The custom designed readout electronics allows for operation at sufficiently low laser intensities in order to prevent significant degradation of the performance of the amorphous silicon sensors under illumination with laser light.

Keywords— Silicon strip sensors, amorphous silicon, laser beams, laser diodes, alignment monitoring

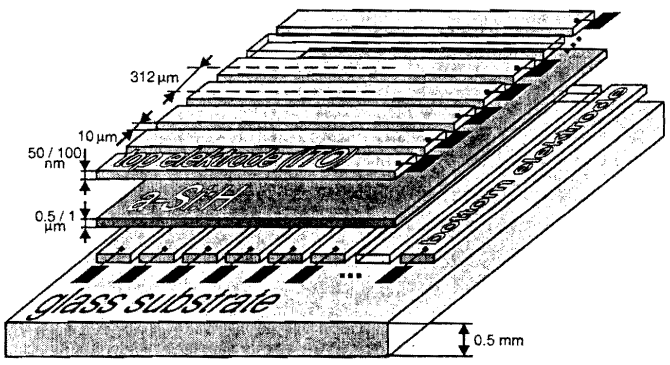

Fig. 1. Structure of the ALMY sensors.

I. Introduction

Novel semitransparent optoelectronic position sensors, the 'ALMY sensors,' have been developed for high-precision multi-point position and angle measurements of collimated laser beams over a large measurement range [1]-[5]. The ALMY sensors consist of a thin layer of hydrogenated amorphous silicon (a-Si:H) of $0.3 - 1$ μm thickness deposited on a 0.5–1 mm thick polished glass substrate between two electrode layers of indium-tin oxide (ITO) of $50 - 100$ nm thickness which are transparent for the visible light spectrum (see Fig. 1). A sensor module with readout electronics is shown in Fig. 2.

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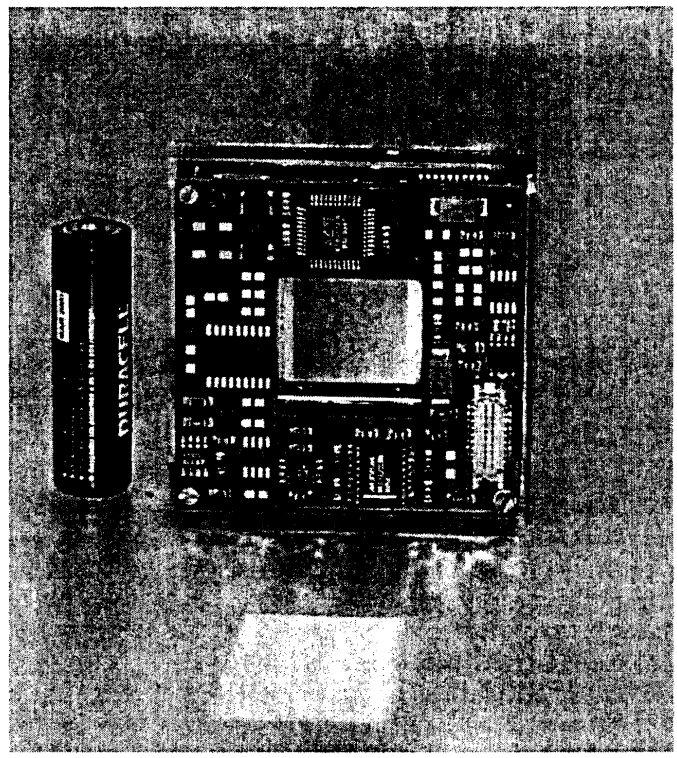

Fig. 2. ALMY sensor module with readout electronics. The transparent sensor is glued across a cutout in the 60 mmm × 60 mm size readout electronics boards. The bond pads of the strip electrodes outside the sensitive and transparent area are visible.

The thin films are produced by chemical vapour deposition from the plasma phase. In contrast to amorphous silicon solar cells which are made with similar techniques, the two electrode layers of the sensors are segmented into orthogonal arrays of 64 strips with 312 μm pitch and a width of 300 μm covering the whole sensor area of 20×20 mm^2. Larger and smaller sensor sizes are possible.

Laser diodes coupled to single-mode optical fibers with collimator optics are used to produce collimated laser beams with gaussian profile at wavelengths of 690 nm or

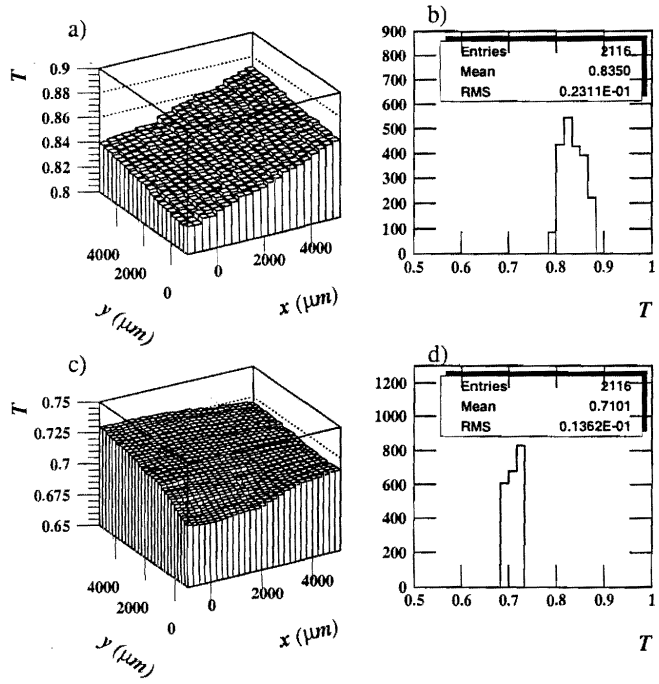

Fig. 3. Transmittance T of a typical ALMY sensor at wavelengths of (a and b) 780 nm and (c and d) 690 nm. Shown are (a and c) the uniformity of the transmittance as a function of the laser beam position (x, y) on the sensor surface and (b and d) the distribution of the transmittance from a scan of the sensor (see text).

780 nm near the end of the absorption spectrum of a-Si:H. The two-dimensional centroide of the gaussian laser beam profile projected on the sensor surface can be determined from the measured photo current distributions on the top and bottom strips with an accuracy of on the order of 1 μm over the whole measurement range [1]-[5].

At 690 nm and 780 nm laser wavelength, transmittances of the sensors of 70−75% and of 80−90%, respectively, have been reached (see Fig. 3). The high transmittance of the sensors for visible light allows for multiple measurements of the same laser beam by more than 10 sensors positioned along the beam. Such systems consisting of diode lasers and ALMY sensors have a variety of applications in the alignment monitoring systems of high energy physics experiments [6]-[12]. For applications in high energy physics it is of special importance that the position resolution of the amorphous silicon sensors does not deteriorate in high magnetic fields [1]-[4] and under high radiation doses [5] in contrast to many crystalline silicon devices. The sensors have also been tested in industrial applications.

In this paper we give an update on the sensor development and performance and report about studies of the long-term stability and radiation hardness of the ALMY sensors. For the previously published results, the naked sensors have been fabricated by Heimann Optoelectronics in Wiesbaden, Germany. The results reported in this paper, with the exception of the long-term stability tests under illumination (see below), have been performed with sensors fabricated in a new facility at the Institut für Physikalische Elektronik at the University of Stuttgart, Germany.

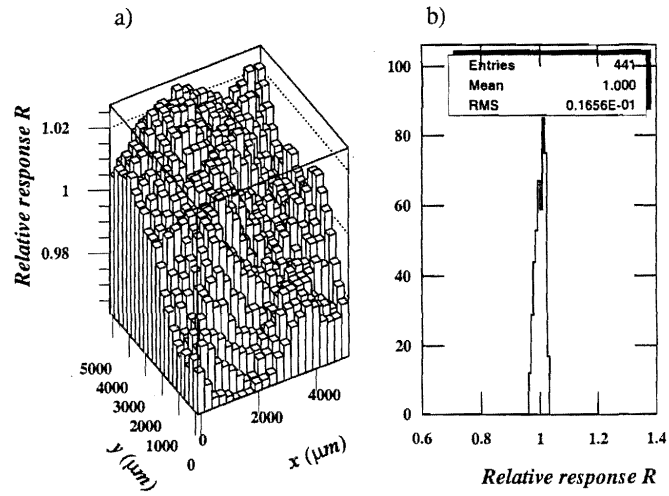

Fig. 4. Relative photo current response R (average normalized to one) of the same ALMY sensor as in Fig. 3. Shown is (a) the response as a function of the laser beam position (x, y) on the sensor surface and (b) the distribution of the response from a scan of the sensor (see text).

II. Readout electronics

For each measurement of the laser beam position, the 2×64 strip electrodes of an ALMY sensor are read out by custom designed readout electronics. The sensors are glued and wire bonded to readout boards which have cutouts for the active area of the sensors (see Fig. 2). On the boards, the analog signals of all strips are multiplexed, amplified by a common current-voltage converter, digitized and transmitted to a PC for online analysis.

Previously published test results [5] have been obtained using custom designed integrated readout electronics in CMOS technology [13], [14] with interfaces to the VME bus or to the PC serial port. Recently a new version of the readout electronics has been developed using only commercial components and consisting of stacked analog and digital boards which both have a size of 60 mm × 60 mm (see Fig. 2). The sensors can be individually read out via a RS 485 interface. An additional interface board of also 60 mm × 60 mm size contains an interface converter from the PC standard serial RS 232 interface to RS 485 and a "laser controller" which allows for switching on and off the diode laser and for adjusting the laser power. The interface board allows for connecting up to 30 sensors and other laser controllers to the standard PC serial port.

Switching on the laser beam only during the measurement time guarantees minimum sensor illumination time (see below). The time for reading out the photo current values of all strips into the internal memory of the sensor module is 10 ms. The data are read twice and averaged in order to suppress noise resulting in a total measurement time of 20 ms. All sensors in the laser beam connected to one RS 485 interface can do the measurement simultaneously. After the laser is switched off, the data are transferred from the local sensor memories to the PC sequentially which takes about 20 ms for each sensor.

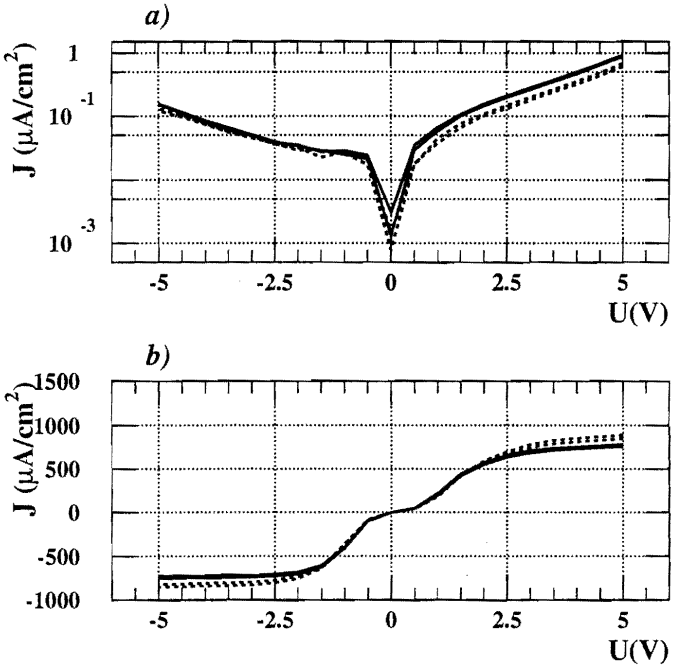

Fig. 5. Current-voltage characteristics of amorphous silicon photo diodes (a) without and (b) with light exposure of arbitrary intensity before (full lines) and after (dashed lines) irradiation with 10^{14} neutrons/cm^2.

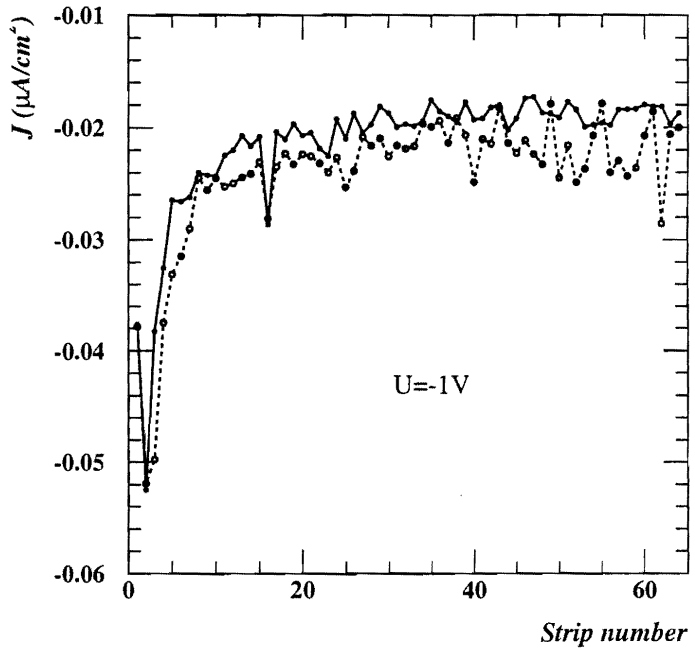

Fig. 6. Dark current as a function of strip number for the same ALMY sensor as in Fig. 5 at the nominal bias voltage of 1 V before (full line) and after (dashed line) irradiation with 10^{14} neutrons/cm^2.

Both readout electronics versions as well as the laser diodes with optical fibers and collimator optics have been tested up to fluences of 10^{13} neutrons/cm^2 (1 MeV neutrons equivalent). No deterioration of the performance has been observed. The readout electronics did not survive, however, a fluence of 10^{14} neutrons/cm^2.

III. Sensor performance

The reflectivity of the sensor surfaces in the wavelength range of 690–780 nm has been minimized by optimizing the a-Si:H and ITO layer thicknesses on the front surface and by using state-of-the-art antireflective coating on the back side of the glass substrate in order to increase the average transmittance for the laser beam and to suppress interference patterns in the sensor response and in the transmittance across the sensor surface which can be caused by finite wedge angles of the glass substrate. This design leads to a sufficiently uniform distribution of the transmittance (see Fig. 3) and of the light absorption or sensor response, respectively (see Fig. 4), over the sensor surface such that the traversing laser beam profile remains undistorted and the linearity of the position measurement is not degraded. Also, laser diodes with short longitudinal coherence length are used in order to minimize interference effects in the glass substrate.

The uniformity of the sensor parameters is tested by scanning the surface with a laser beam of about 3 mm diameter (3σ) using a two-dimensional translation stage with stepping motors of 1 μm absolute positioning accuracy on which the sensor is mounted. The transmittance of the test sensor and the deflection of the traversing laser beam are measured with two additional ALMY sensors at known distances using the measurement without test sensor as reference. The deflected beam position is measured at two distances behind the test sensor in order to disentangle the angular beam deflection from the parallel displacement of the beam in the case of non-perpendicular incidence. Care is taken to prevent deflections of the laser beam due to temperature gradients in the air.

The top electrodes of the sensors act as Schottky contacts. The photo diode characteristics of a strip crossing on a typical sensor is shown in Fig. 5. The sensors are operated at bias voltages of $1-2$ V. In this voltage range, the dark currents are very small, only $10^{-7}-10^{-8}$ A/cm^2 (see Figs. 5 and 6), while the sensitivity of the sensors is approximately 0.1 A/W at 690 nm and 0.01 A/W at 780 nm for a 1 μm thick amorphous silicon layer. The readout electronics saturates at peak laser intensities of about 10 mW/cm^2 at 690 nm and 100 mW/cm^2 at 780 nm corresponding to a maximum strip current of 1 μA. The strip currents have been limited to 1 μA in order to limit the voltage drop along the strips which have non-negligible resistance and thus to prevent a significant sensitivity variation across the sensor surface.

The large signal-to-noise ratio of > 1000 allows for a local position resolution of the sensors of better than 1 μm (for a strip pitch of 312 μm and laser beam diameters of > 2 mm) with a dynamic range in signal heights from 0.1 to 1 times

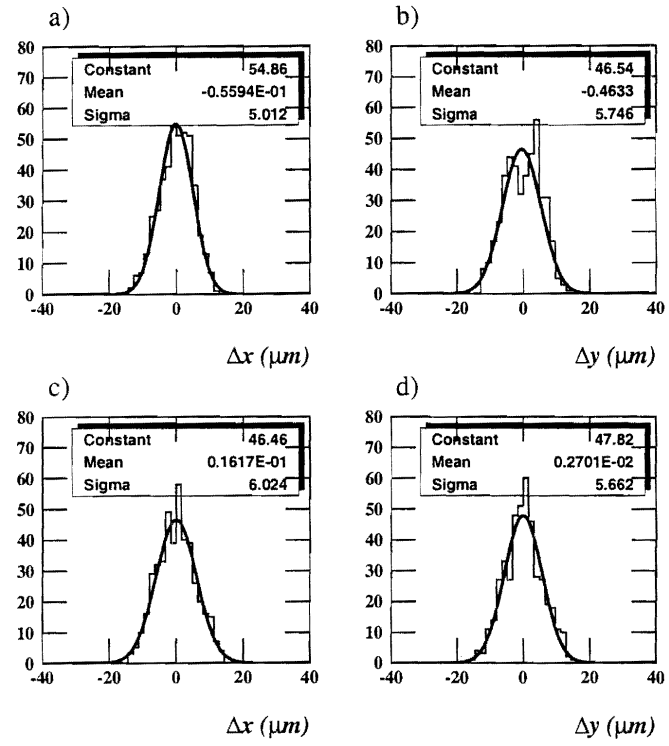

Fig. 7. Position measurement accuracy of the same ALMY sensor as in Fig. 3 in the two sensor coordinates x and y (a and b) before and (c and d) after irradiation with 10^{13} neutrons/cm^2. Shown are the distributions of the differences Δx and Δy between the measured and the true laser beam coordinates (see text).

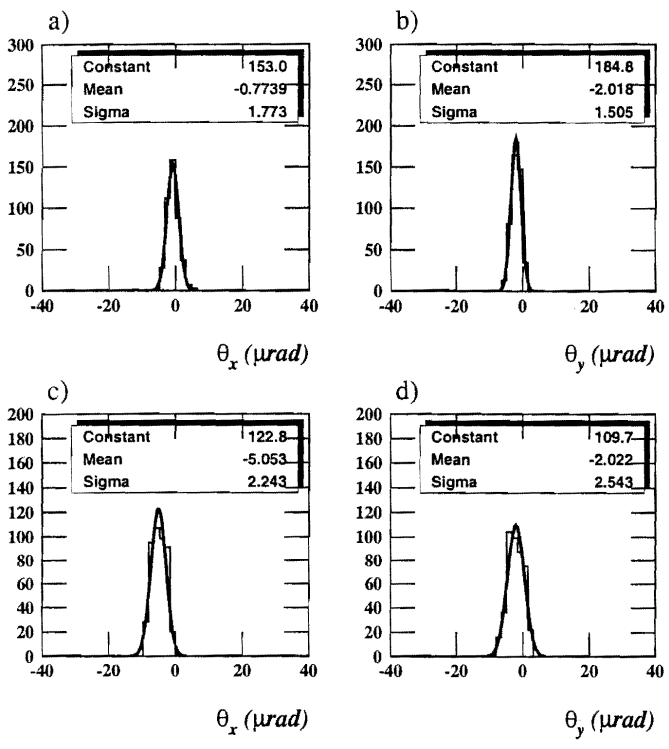

Fig. 8. Laser beam deflection angles Θ_x and Θ_y in the two coordinates transverse to the beam for the same ALMY sensor as in Fig. 3 (a and b) before and (c and d) after irradiation with 10^{13} neutrons/cm^2.

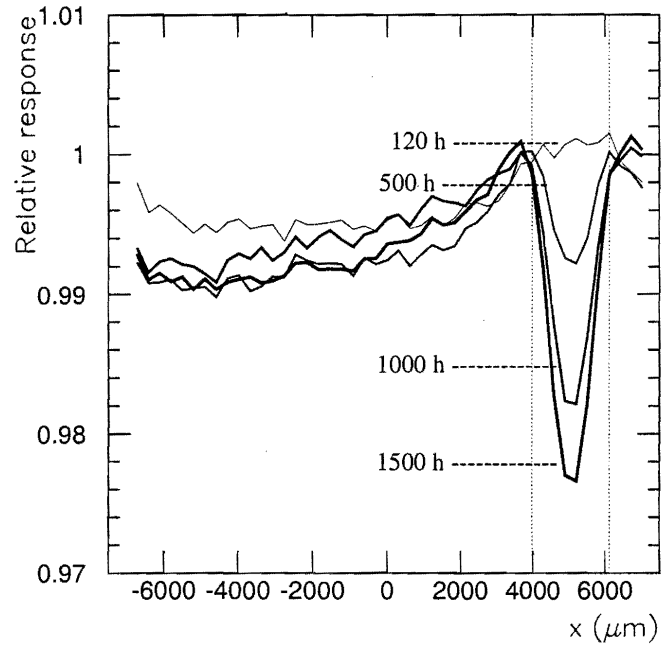

Fig. 9. Local degradation of the relative photo current response of an ALMY sensor measured with laser scans (see text) after 120, 500 1000 and 1500 hours of continuous illumination with a 690 nm laser beam of 3 mm diameter (3σ) and 10 mW/cm^2 peak intensity under dark conditions. The local sensitivity loss follows the gaussian profile of the laser beam.

the saturation level. The local position measurement is limited by the pointing stability of the laser beam.

The linearity of the position measurement over the whole sensitive area depends on the uniformity of the sensor response which can be achieved in the fabrication process (see Fig. 4). About 200 sensors with different sensor layers, glass substrates and antireflective coating have been produced and tested. With antireflective coating of the glass substrate, a position resolution over the whole sensor surface of 1 μm has been achieved [5]. The typical position resolution of sensors with antireflective coating is better than 5 μm (see Fig. 7). The resolution in each of the two sensor coordinates x and y is determined as the width of the distribution of the difference between the measured positions and the true positions given by the stepping motor.

In order to minimize the deflection of the traversing laser beam and the variation of the deflection over the whole sensor surface, specially polished glass wafers with flat parallel surfaces are used which do not get deformed during the antireflective coating of the wafers (see [5]) and during sensor production at temperatures of up to 200°C. The average laser beam deflection and the uncertainty in the deflection are below 5 μrad for the complete sensors (see Fig. 8).

IV. Long-term stability

From the study of amorphous silicon solar cells, it is well known that the photo current response of a-Si:H deteriorates under illumination [15]. A local degradation of the sensitivity and thus of the position measurement accuracy has been observed for the ALMY sensors when they

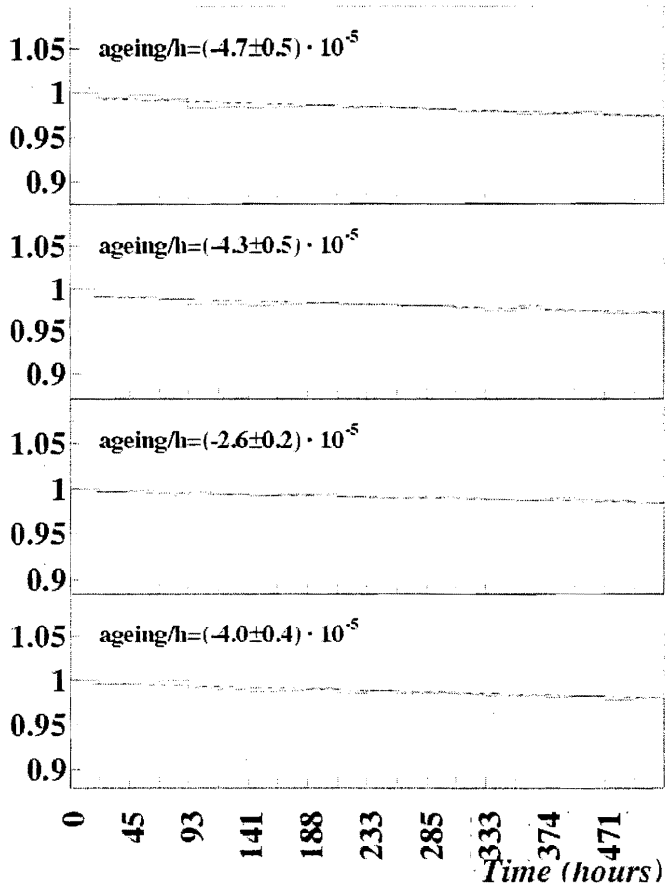

Fig. 10. Relative photo current response of four ALMY sensors monitored as a function of time at the peak position of the laser beam profile during continuous illumination over 520 hours with a 780 nm laser beam of 3 mm diameter (3σ) and 100 mW/cm^2 peak intensity under dark conditions.

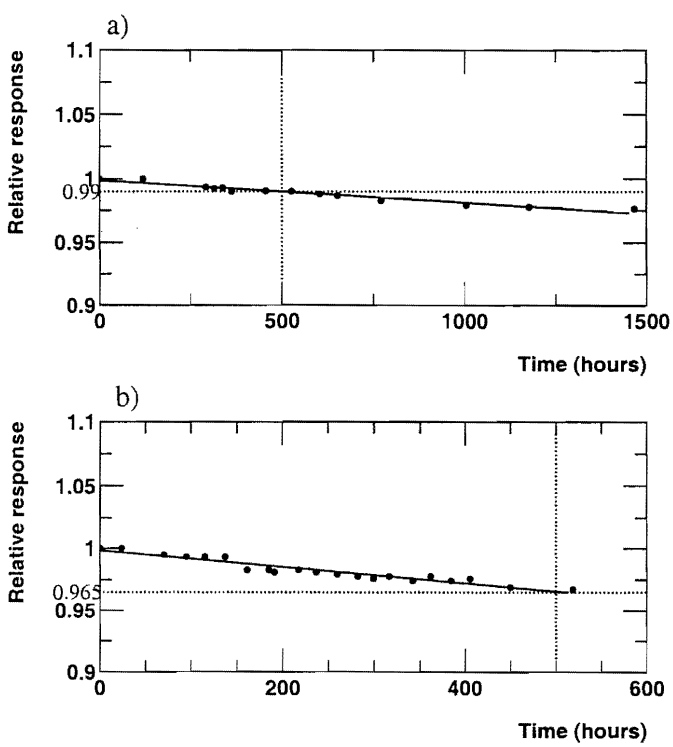

Fig. 11. Time dependence of the relative photo current response (as in Fig. 10) of an ALMY sensor during continuous illumination (a) with a 690 nm laser beam of 3 mm diameter (3σ) and 10 mW/cm^2 peak intensity under dark conditions and (b) with a 780 nm laser beam of 3 mm diameter and 100 mW/cm^2 peak intensity in the presence of daylight.

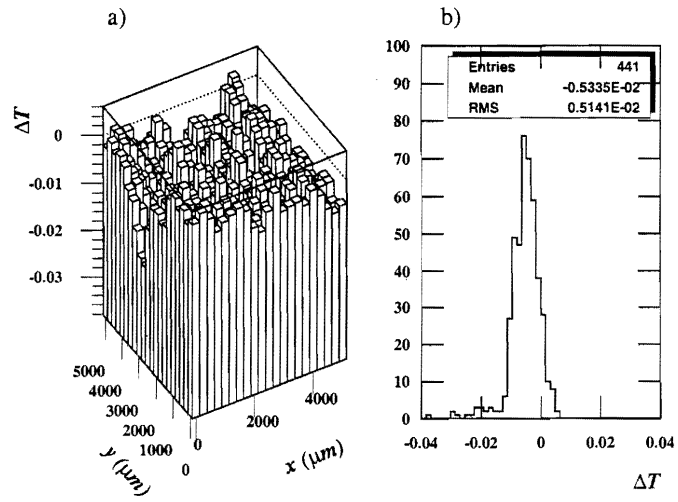

Fig. 12. Change ΔT of the transmittance of the ALMY sensor in Fig. 3 at a wavelength of 780 nm after irradiation with 10^{13} neutrons/cm^2 (denotations as in Fig. 3).

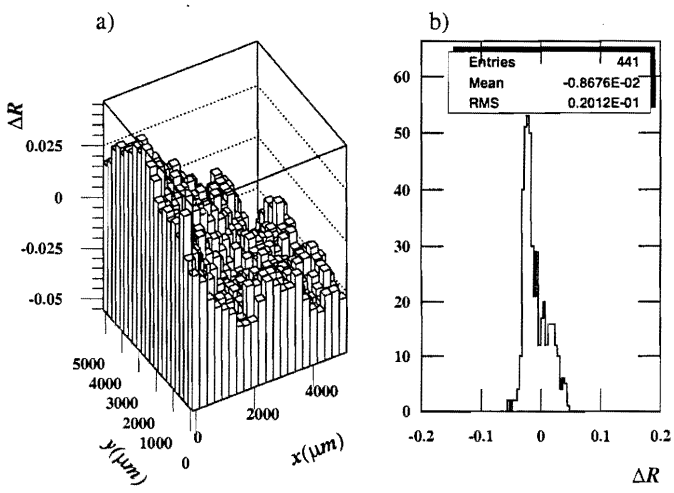

Fig. 13. Change ΔR of the relative photo current response of the ALMY sensor in Fig. 4 after irradiation with 10^{13} neutrons/cm^2 (denotations as in Fig. 4).

are continuously illuminated by a laser beam at constant position [5]. The position sensitivity of the ALMY sensors allows for detailed studies of the dependence of the degradation effect on the laser intensity and wavelength by monitoring as a function of time with laser scans the local sensitivity minimum created at the peak of the laser beam profile with respect to the rest of the sensor area (see Fig. 9). With this method, one does not have to rely on a precise calibration of the laser intensity and profile when probing sensitivity variations over a long time period.

The readout electronics is designed such that the maximum signal height below saturation is reached for 10 mW/cm^2 peak intensity at 690 nm wavelength and for 100 mW/cm^2 peak intensity at 780 nm wavelength, respectively. The sensors are operated in a housing shielding them from daylight which otherwise would saturate them. The local degradation of the sensor response as a function

of time is shown in Figs. 10 and 11a for the two operation modes. The degradation rate is constant at the relatively low laser intensities below saturation. After 500 hours of continuous illumination at the above operating conditions of the sensors, the sensitivity loss at the peak is $1.5 - 2.5\%$ at 780 nm (depending on the sensor) [5] and 1% at 690 nm. In the latter case, 2.5% degradation is reached after 1500 hours of illumination. The results at different wavelengths support the concept that the degradation rate depends on the light absorption in the amorphous silicon, which varies with the wavelength, rather than just on the illumination intensity.

A 2.5% local sensitivity loss is of similar size as the observed sensitivity variations on the sensors after fabrication (see Fig. 4). It corresponds to a local absolute position measurement error of ± 5 μm [5]. Therefore there is no significant deterioration of the sensor performance during at least 500 hours of continuous illumination in the same spot at the maximum signal height. The sensors will only be illuminated by the laser beam while they are read out during a measurement.

The illumination with a 780 nm laser beam of 100 mW/cm^2 peak intensity has been repeated in the presence of uniform illumination with daylight which produces a typical signal current close to saturation. Fig. 11b shows, as a function of time, the additional local degradation of the sensitivity at the laser beam position relative to the response of the rest of the sensor which is illuminated with daylight only. After 500 hours, the additional local degradation is 3.5% exceeding the degradation observed with laser illumination under dark conditions. The dependence of the degradation rate on the light absorption appears to be non-linear as predicted by models of the aging of hydrogenated amorphous silicon under illumination [16].

V. Radiation hardness

Amorphous silicon sensors are expected to be more tolerant against particle irradiation than crystalline silicon devices. This is of particular importance for applications in the optical alignment monitoring systems of high energy physics experiments [6]-[12]. Studies have been performed of the performance of ALMY sensors from different production batches (different a-Si:H thickness, different glass substrates) after irradiation with neutrons. The irradiation with neutrons of 0.75 MeV mean energy has been performed at the Prospero reactor of CEA in France.

In Figs. 5 and 6, the current-voltage characteristics and the dark currents at the operating bias voltage of sensors from the current production after optimization of the a-Si:H thickness and of the glass substrate are compared before and after irradiation with a neutron fluence of 10^{14} neutrons/cm^2 (1 MeV neutrons equivalent). No degradation of the current-voltage characteristics was observed and, in particular, there is no significant increase of the dark currents up to this high neutron fluence.

In Figs. 7, 8, 12 and 13, the position resolution, laser beam deflection, transmittance and photo response of the sensors of the current production equipped with the new readout electronics (see Fig. 2) are compared before and after irradiation with a neutron fluence of 10^{13} neutrons/cm^2 (1 MeV neutrons equivalent). There is no significant degradation of the performance parameters of the sensors, including the electronics, up to this neutron fluence. The same is true for sensors from previous productions with thicker a-Si:H layers and different glass substrates equipped with the previous integrated electronics [5].

Sensor modules with readout electronics have not yet been tested with neutron fluences above 10^{13} neutrons because the electronics is not expected to survive. The transmission and beam deflection properties of the sensors and of the glass substrates alone have been tested without readout electronics up to neutron fluences of 10^{14} neutrons/cm^2 (1 MeV neutrons equivalent). No significant deterioration in the average parameters is seen for the new sensors as well as for the ones from previous productions and for all types of glass substrates used. The variation of the transmittance and of the angular deflection over the sensor surface becomes slightly larger with increasing neutron fluence.

The radition hardness results are confirmed by irradition tests of ALMY sensors from the earlier production at Heimann Optoelectronics by other groups. The sensors (without electronics) were shown to survive ^{60}Co γ irradiation of 10 MRad and a neutron fluence of $1.1 \cdot 10^{15}$ neutrons/cm^2 without significant changes in transmittance and deflection [17]. A degradation of the sensor response of 10%, 30% and 40% was observed after the γ irradiation and after additional neutron irradiation with 10^{14} and $1.1 \cdot 10^{15}$ neutrons/cm^2, respectively, which is not far outside the sensor production tolerances and does not compromise the functionality and the position resolution of the sensors.

VI. Conclusions

Transparent amorphous silicon position sensors ('ALMY sensors') have a wide range of applications in optical alignment monitoring systems. The sensors fulfill the particularly high demands on the position resolution, measurement range and radiation hardness for applications in high energy physics experiments. The performance of the sensors has been further optimized and verified in extensive tests. A new larger-scale sensor production is under preparation. The effect of degradation of the sensitivity of the amorphous silicon under illumination and the radiation hardness of the sensors including readout electronics under neutron irradiation have been studied in detail. Deteriorations of the sensor performance due to these effects were found to be negligible for the foreseen applications.

VII. References

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