Adjustable ultraviolet-sensitive detectors based on amorphous silicon

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Thin-film detectors made of hydrogenated amorphous silicon (a-Si:H) and amorphous silicon carbide (a-SiC:H) with adjustable sensitivity in the ultraviolet (UV) spectrum were developed. Thin PIN diodes deposited on glass substrates in N–I–P layer sequence with a total thickness of down to 33 nm and a semitransparent Ag front contact were fabricated. The optimized diodes with a 10 nm Ag contact exhibit spectral response values above 80 mA/W in the wavelength range from 295 to 395 nm with a maximum of 91 mA/W at 320 nm. For longer wavelengths, the spectral response drops by 50% at 450 nm. Increasing the thickness of the Ag front contact leads to a narrowing of the spectral response at around 320 nm, which allows the adjustment from a broad UV to a selective UV–B-sensitive detector. [DOI: 10.1063/1.1365948]

Hydrogenated amorphous silicon (a-Si:H) and its alloys (a-SiC:H, a-SiGe:H) exhibit high photosensitivity in the wide spectral range from ultraviolet (UV) to infrared. Low-cost fabrication and low-temperature deposition over large areas by plasma-enhanced chemical-vapor deposition (PECVD) make them attractive for realization of large-area devices and large-area arrays with arbitrary shape and even onto flexible substrates.[1] a-Si:H-based photodetectors with enhanced sensitivity in the near UV, down to the wavelength (λ) of 350 nm,[2,3] or with sensitivity in vacuum UV ($\lambda < 200$ nm),[4] have been reported, but no detector so far has covered the range of UV–A and UV–B. In this spectral range, the development of a low-cost detector is of great interest for monitoring of skin exposure to harmful UV radiation. Reference 2 dealt with devices in superstrate configuration, while Ref. 3 investigated devices in substrate configuration. Both of them showed only a weak suppression of the responsivity in the visible range. The device in Ref. 4 exhibited a too strong suppression of the spectral response for wavelengths above 300 nm since it was optimized for application in the vacuum UV range.

In this letter, we demonstrate thin-film diodes made of a-SiC:H/a-Si:H exhibiting good sensitivity in the UV and suppressed sensitivity in the visible spectrum range. Its selectivity and/or sensitivity can be adjusted with either thickness variation of both, front contact layer and semiconducting amorphous layers, or variation of optical properties of active layers. In this letter, the band gap of the used layers was kept constant.

Figure 1 shows the cross section of a detector in sandwich configuration. On a Corning glass substrate a transparent conductive oxide (ZnO:Al) layer[5] was sputtered. ZnO:Al was used as the back contact, since a bad reflector/good transmitter of the visible light is desired to suppress the detector's sensitivity in the visible-light spectrum. The amorphous-silicon-based layers were deposited in a multichamber PECVD system at a substrate temperature of 200 °C, a pressure between 500 and 1000 mTorr, and a radio-frequency (13.56 MHz) power density of 40–52 mW/cm^2. PIN diodes were deposited in a N–I–P layer sequence. N- and P-type doped layers were realized by adding phosphine and trimethyl boron in the deposition gas mixture of SiH_4 and H_2, respectively. P and I layers were made of a-SiC:H by adding methane in the deposition gas mixture. For the optical band gap E_{opt} of individual layers (as indicated in Fig. 1), we used $E_{3.5}$, i.e., the energy where the absorption coefficient amounts to $10^{3.5}\,cm^{-1}$. The values were taken from optical reflection and transmission measurements, using separately prepared samples. As a front contact, a thin semitransparent metal (Ag) layer of 10 nm was evaporated. The total area of the device was 1 cm^2.

The spectral response (SR) and quantum efficiency (QE) of the detectors have been measured in air in the wavelength range 200–800 nm, using a photon flux of around 10^{14} photons/(cm^2 s). The photocurrent of the detectors was measured by a lock-in technique.

Figure 2 shows the spectral response under zero bias for three PIN diodes (designated as samples A, B, and C) with different layer thicknesses (see Table I). Decreasing the

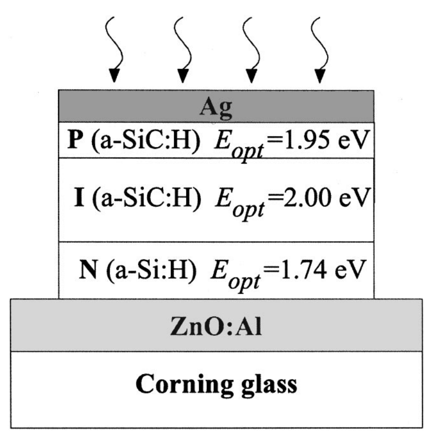

FIG. 1. Schematic view of Ag/P–I–N/ZnO:Al diodes. The material composition and the optical band-gap values are also indicated.

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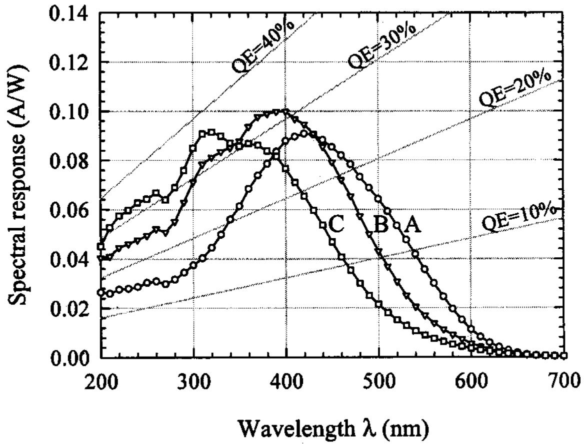

FIG. 2. Spectral response of three *PIN* diodes (samples A, B, and C) with different layer thicknesses (see Table I). Straight lines indicate quantum-efficiency equilines.

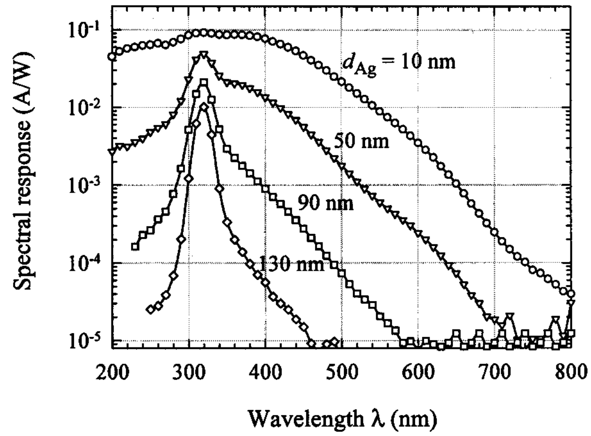

FIG. 3. Spectral response of the *PIN* diode (sample C) with a semitransparent Ag front contact of different thicknesses.

I-layer thickness of the *PIN* diode from 50 nm (sample A) to 30 nm (sample B), the peak and also the long-wavelength cutoff shift toward the near-UV region. Additionally, for sample B a significant improvement of sensitivity in the UV occurs due to the decrease of *P*-layer thickness. The reduction of *P*-layer thickness enables that more photons reach the *I* layer, where the collection efficiency of the photogenerated carrier is much higher. Ideally, the *P* layer should be as thin as possible, but still thick enough to ensure sufficient charge for building up the electric field across the *PIN* diode. Reduction of the *P* layer to only 3 nm and the *I* layer to only 10 nm (sample C) results in further improvement of the spectral response in the UV range and its additional suppression in the visible range. This thin diode (sample C) with a total thickness of 33 nm exhibits a spectral response above 80 mA/W in the wavelength range from 295 to 395 nm with a maximum of 91 mA/W at $\lambda = 320$ nm. A 50% drop off from the maximum for longer wavelengths occurs at 450 nm. From QE equilines in Fig. 2 we can see that this device exhibits QE values of over 30% almost in the whole nonvacuum UV range, i.e., from 200 to 360 nm, with the maximum of 36.3% at 310 nm. These are excellent values for *a*-Si:H-based detectors in substrate configuration.

By decreasing the thickness of the *PIN* diodes (already below 100 nm), the yield of diodes with good performance is limited due to shunts, which hinder low reverse dark currents.[6] According to scanning electron microscopy measurements, we suppose that the origin of the shunts are irregularities like holes and spikes, as well as contamination of the glass and the ZnO:Al substrate. As-grown ZnO:Al layers are flat, exhibiting a δ_{rms} roughness of around 7 nm measured by atomic-force microscopy. Under optimized sputtering and cleaning conditions, a yield of around 50% is reached. Hence, for all samples (A–C) dark current densities below 10^{-9} A/cm^2 are achieved at 100 mV reverse bias.

Since the absorption coefficient of Ag exhibits a local minimum at the wavelength of 320 nm,[7] this property can be utilized for a selective UV detector. Therefore, we have investigated the effect of the thickness of the semitransparent front contact on the device behavior of our 33-nm-thick *PIN* diode (sample C). We varied the thickness of the Ag front contact from the initial 10 nm to 130 nm by three successive depositions of 40 nm Ag per run. Figure 3 shows in a log scale of response the shrinking of the spectral response with increasing Ag front-contact thickness. In this way, its full width at half magnitude can be varied from 250 nm down to 20 nm (see Table II), while the maximum of the spectral response at $\lambda = 320$ nm loses less than one order of magnitude (only 90%).

In summary, we have realized amorphous-silicon-based detectors with adjustable sensitivity in the ultraviolet spectrum and with suppressed sensitivity in the visible range. Very thin *PIN* diodes deposited in a *N–I–P* sequence exhibit low reverse current densities. The best device performance was achieved with a 33-nm-thick *PIN* diode having a maximum spectral response of 91 mA/W at $\lambda = 320$ nm. Adjustable selectivity of the detectors with a peak at $\lambda = 320$ nm was achieved by varying the thickness of the Ag front semitransparent contact. Such an approach allows the variation of the spectral sensitivity from a broad UV to a selective UV–B spectrum.

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TABLE I. Layer thicknesses for different samples.

Thickness	ZnO:Al (nm)	*N* (nm)	*I* (nm)	*P* (nm)
Sample A	80	10	50	10
Sample B	80	10	30	5
Sample C	80	20	10	3

TABLE II. Effect of Ag front-contact-thickness variation on the maximum spectral response value and selectivity [full width at half magnitude (FWHM)] of sample C.

Ag thickness (nm)	10	50	90	130
SR_{max}(mA/W)[a]	91	49	21	10
FWHM (nm)	250	43	32	21

[a]At $\lambda = 320$ nm.

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