

High-Sensitivity and No-Crosstalk Pixel Technology for Embedded CMOS Image Sensor

Masayuki Furumiya, Hiroaki Ohkubo, Yasunori Muramatsu, Susumu Kurosawa, Fuyuki Okamoto, Yuki Fujimoto, and Yasutaka Nakashiba

Abstract—A high-photosensitivity and no-crosstalk pixel technology has been developed for an embedded active-pixel CMOS image sensor, by using a 0.35- μm CMOS logic process. To increase the photosensitivity, we developed a deep p-well photodiode and an antireflective film, consisting of Si_3N_4 film, for the photodiode surface. To eliminate the high voltage required for the reset transistor in the pixel, we used a depletion-type transistor as the reset transistor. The reset transistor also operates as an overflow control gate, which enables antiblooming overflow when excess charge is generated in the photodiode by high-illumination conditions. To suppress pixel crosstalk caused by obliquely incident light, a double-metal photoshield was used, while crosstalk caused by electron diffusion in the substrate was suppressed by using the deep p-well photodiode. A 1/3-in 330-k-pixel active-pixel CMOS image sensor was fabricated using this technology. A sensitivity improvement of 110% for 550-nm incident light was obtained by using the deep p-well photodiode, while an improvement of 24% was obtained by using the antireflective film. The pixel crosstalk was suppressed to less than 1% throughout the range of visible light.

Index Terms—Active-pixel sensor, antireflective film, CMOS image sensor, crosstalk, photodiode, photoshield, reset transistor, sensitivity.

I. INTRODUCTION

THE development of image sensors based on CMOS logic processes has been the subject of several recent studies [1]–[4]. We refer to such image sensors—that is, active-pixel CMOS image sensors—as embedded CMOS image sensors. They are attractive devices because of their low power consumption and applicability for on-chip signal processing. However, the characteristics of these devices as photosensors are inadequate for some applications, and this particularly applies to CMOS image sensors with very small pixels, for example, such as those in the several-micrometer range. In such small pixels, the signal-to-noise ratio (S/N) inevitably decreases, while crosstalk between neighboring pixels increases. Therefore, there is a strong demand for pixels that are highly photosensitive, have low noise levels, and can be fabricated by standard CMOS logic processes.

One effective way to develop a high-sensitivity photodiode for use as an image sensor is to deepen the photoconversion region. Deep-photoconversion-region photodiodes with high photosensitivity have already been reported for charge-coupled-device (CCD) image sensors [5], [6]. On the other hand, for CMOS

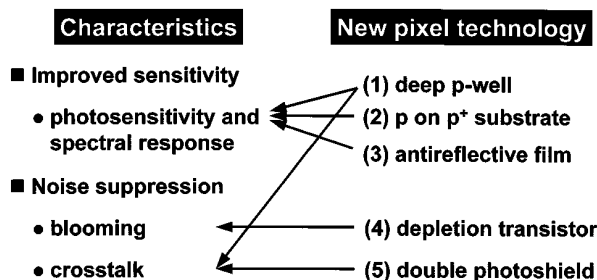


Fig. 1. Proposed solutions, which fulfill the requirements for small-pixel CMOS image sensors.

image sensors, the shallow high-concentration p-well used for CMOS logic circuits is not suitable for obtaining a deep photoconversion region.

Another approach for improving photosensitivity is to introduce an antireflective film at the photodiode surface. An antireflective film consisting of Si_3N_4 film has also been reported for a CCD image sensor [7]. In this sensor, the antireflective-film process requires an extra mask to form the Si_3N_4 film. This unavoidably increases fabrication costs.

To reduce the pixel size for CMOS image sensors, we started with a low-noise pixel. A pinned photodiode, which has a p^+ region at the photodiode surface, was used because the noise caused by its surface state was suppressed [8]–[10]. The other two types of noises, blooming noise and crosstalk noise, should also be reduced [11], [12]. These two noises especially degrade reproduced images especially under high-illumination conditions.

We have thus developed a new pixel technology to overcome the above-mentioned problems, and we have obtained a high-performance active-pixel CMOS image sensor. Fig. 1 shows our solutions, which fulfill the requirements for small-pixel CMOS image sensors. The left side of Fig. 1 lists the requirements for the pixel characteristics. The principal requirements here are improved sensitivity and lower noise. To meet these requirements, we applied five techniques in fabricating the pixel: (1) deep p-well photodiode; (2) p-on- p^+ epitaxial substrate; (3) antireflective film; (4) depletion transistor as the reset transistor; and (5) double-metal layer photoshield. We explain and discuss these techniques in the following sections.

II. NEW PIXEL TECHNOLOGY

Fig. 2 shows a cross-sectional view of the structure of our new pixel, which includes a photodiode and a reset transistor.

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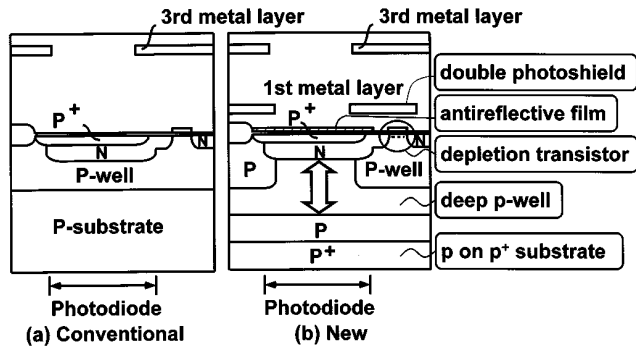


Fig. 2. Cross-sectional view of (a) a conventional pixel structure and (b) the new pixel structure.

A conventional photodiode is formed in a p-well, which is the same type of p-well as that used in CMOS logic circuits. The impurity profile of this type of p-well has a shallow depth and a high concentration. This type of p-well is not suitable for our purposes because of its shallow photoconversion region. The p^+ region of the photodiode surface suppresses the noise caused by its surface state.

To increase the photosensitivity, we used a deep low-concentration p-well (deep p-well) for the photodiode. The deep p-well forms a deep depletion region and can be used as the photoconversion region. A p-on- p^+ epitaxial substrate is used to fit the luminous response of the photodiode to the required spectral response. We have also developed an antireflective film for the photodiode surface. This film decreases the reflection caused by the difference in refractive index between the SiO_2 and Si at the photodiode surface. One advantage of adopting an antireflective film for CMOS image sensors is that it does not increase the number of masks required.

Conventional photodiodes use an enhanced transistor as the reset transistor. This type of transistor requires a gate voltage of over 3.3 V, e.g., 4.5 V during photodiode reset. To eliminate the need for high-voltage circuits, we used a depletion transistor as the reset transistor. The depletion transistor also acts as an overflow control when the photodiode is exposed to high illumination.

To suppress crosstalk between pixels, one effective approach is to prevent obliquely incident light from reaching the outside of the photodiode, and another approach is to prevent the diffusion of electrons from pixel to pixel. We developed a double-metal photoshield to reduce the crosstalk caused by obliquely incident light, especially effective for short wavelengths of visible light. The crosstalk caused by electron diffusion, which is generated by the longer wavelengths, was reduced by the deep p-well photodiode.

III. RESULTS AND DISCUSSION

A. Deep p-Well Photodiode for High Sensitivity

Deepening the photo conversion region is one effective way to develop a more highly sensitive photodiode [5], [6]. Hence, we used the deep p-well for the photodiode. The characteristics of the pixel transistor and peripheral circuit transistors are

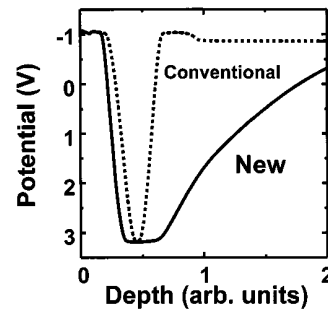


Fig. 3. One-dimensional simulated potential profiles of the new and conventional photodiodes.

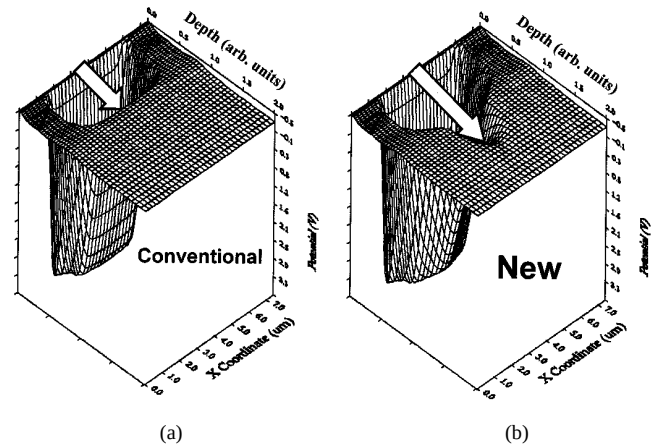


Fig. 4. 2-D simulated potential profiles of (a) a conventional photodiode and (b) the new photodiode.

unchanged, because they use the same p-well as in the conventional pixel sensor.

A one-dimensional (1-D) process-device simulator was used to simulate the photodiode potential so that the effectiveness of the new photodiode structure could be estimated in terms of sensitivity. Fig. 3 shows the simulated potential profiles for the new and conventional photodiodes. The results show that the photodiode using a deep p-well has a deeper photoconversion region than the conventional photodiode. The deeper photoconversion region results in greater photosensitivity because the photoelectrons generated in this deeper region are gathered efficiently. A two-dimensional (2-D) process-device simulator was also used, and the results are shown in Fig. 4. The photoconversion region of the new structure is deep, but this region is limited to the center of the photodiode. The region used by the pixel transistor is not affected by this deep p-well, so the pixel transistor's characteristics are unchanged.

Fig. 5 shows the measured and simulated spectral response of the new and conventional photodiodes. The experimental results are shown by the circles, and the simulated results are shown by the smooth lines. The simulated spectral responses are in good agreement with the measured responses except higher wavelengths. These results show 110% improvement in photosensitivity for 550-nm-wavelength incident light.

We used a p-on- p^+ epitaxial substrate to adjust the spectral response for the relative luminous intensities. The p^+ region under the photodiode helps by recombining the photoelectrons

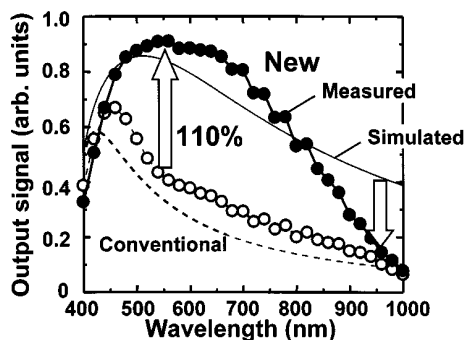


Fig. 5. Measured (shown by circles) and simulated (shown by smooth lines) spectral responses of the new and conventional photodiode structures.

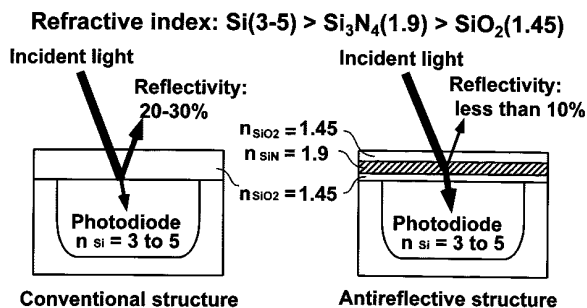


Fig. 6. Incident light reflection at the photodiode surface.

generated in the p^+ region. This cuts the response to near-infrared light (800–1000 nm). Recombination in the p^+ region had not been accounted for in the simulated spectral response. There is, thus, some disagreement between the simulated and measured spectral responses.

B. Antireflective Film

We tested another approach for improving photosensitivity by using antireflective film on the photodiode surface. The antireflective film is investigated by using a CCD image sensor [7]. We refer to results for this device, adapted to a CMOS image sensor.

Fig. 6 shows the surfaces of the conventional and new photodiodes. The conventional photodiode surface is covered by SiO_2 film, which permits about 20%–30% reflection at the interface of the SiO_2 and Si. To suppress the reflection at the interface, we introduced an Si_3N_4 film as an antireflective film. The Si_3N_4 film has a refractive index of 1.9, which can provide antireflective properties because this index is larger than that of SiO_2 (1.45) and smaller than that of Si (3–5). This gradual change in refractive index decreases the reflection in this region.

We calculated the efficiency of the antireflective. Fig. 7 shows the reflectivity dependence on incident light wavelength, as obtained by optical simulation. The results are shown for varying Si_3N_4 thicknesses, with a bottom SiO_2 thickness of 10 nm. The reflectivity is effectively suppressed for Si_3N_4 film thicknesses between 30–70 nm in the range of visible-light wavelengths. The simulation results predict that the reflectivity will be reduced by 75% for a conventional SiO_2/Si structure. For our new photodiode, we chose a Si_3N_4 thickness of 50 nm and a bottom SiO_2 thickness of 10 nm.

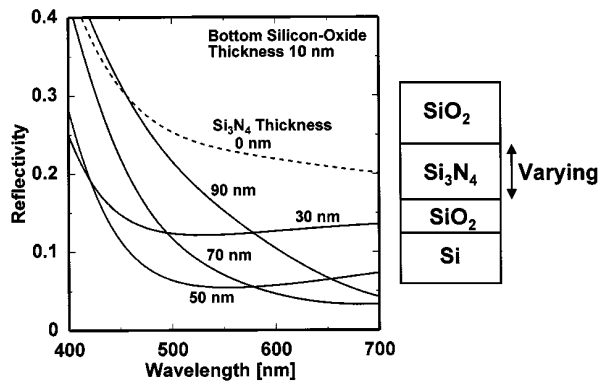


Fig. 7. Simulated reflectivity dependence on incident light wavelength.

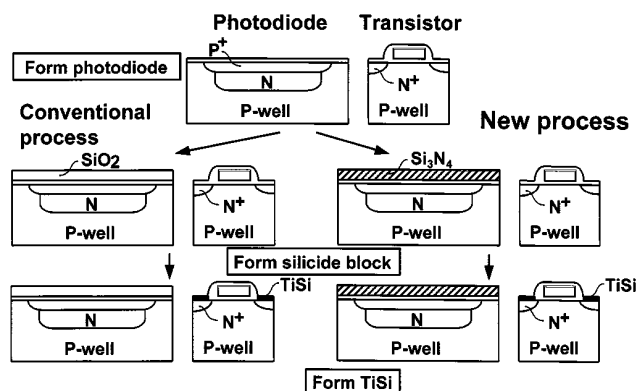


Fig. 8. Fabrication process steps for antireflective film.

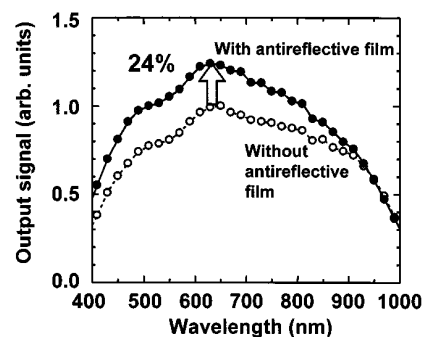


Fig. 9. Measured spectral response for antireflective film.

Fig. 8 shows the process steps for fabricating the antireflective film, as compared to that of the process steps for conventional photodiode. The fabrication process is as follows. First, ion implantation is performed to fabricate the photodiode n -region and surface p^+ region. Next, in the conventional process a thick oxide layer is deposited to prevent silicidation of the photodiode surface, while in the new antireflective-film process, the Si_3N_4 film is deposited to form the antireflective film. The bottom SiO_2 was formed to clamp the photodiode dark current. This antireflection-film process does not require extra masks, so there is no increase in fabrication cost. The Si_3N_4 film thickness can be selected to provide highly efficient antireflectivity.

Fig. 9 shows the spectral response of the new structure, in addition to that of the conventional structure. The photosensitivity

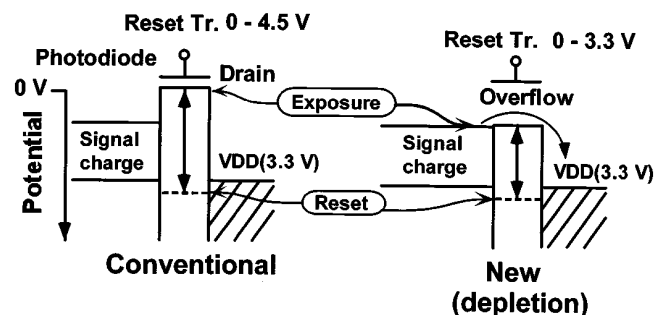


Fig. 10. Potential profile in the region of the reset transistor.

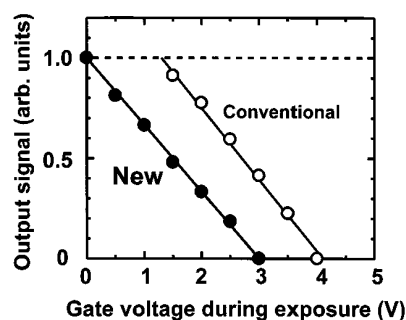


Fig. 11. Measured signal voltage dependence on reset gate voltage during exposure, i.e., the low level of the reset gate voltage.

of the new structure is 24% higher than that of the conventional one throughout the range of visible-light wavelengths. Since a conventional p-type substrate was used for this test, the spectral response is rather different from that in Fig. 5.

C. Depletion-Type Reset Transistor

Fig. 10 shows the potential profile in the region of the reset transistor. Conventional pixels use an enhancement-type transistor as the reset transistor. In the conventional structure, a high voltage of about 4.5 V is required to make the reset transistor reset the photodiode before exposure. This is because the channel potential of the reset transistor must be set to 3.3 V, which is the V_{DD} voltage. To eliminate this need for high-voltage circuitry, we used a depletion-type transistor as the reset transistor. The depletion transistor can also act as an overflow control gate when the photodiode is exposed to high levels of illumination. The potential of the reset transistor in the O-V gate condition is set to the potential level for signal-charge saturation. Excess signal charges generated by high levels of illumination are thus made to flow to the V_{DD} terminal.

Fig. 11 shows the output signal voltage dependence on the low level of the reset gate voltage, or the gate voltage during exposure. The photodiode was exposed to illumination sufficient for photodiode saturation. More than 4 V had to be applied to the conventional reset transistor to reset the photodiode. As this graph shows, a low level of the reset gate voltage of over 4 V is required to bring the signal voltage to zero, which means the reset voltage must be greater than 4 V. The new reset transistor allows the photodiode to be reset at 3.3 V. In addition, it operates as an antiblooming overflow control under the O-V gate voltage condition.

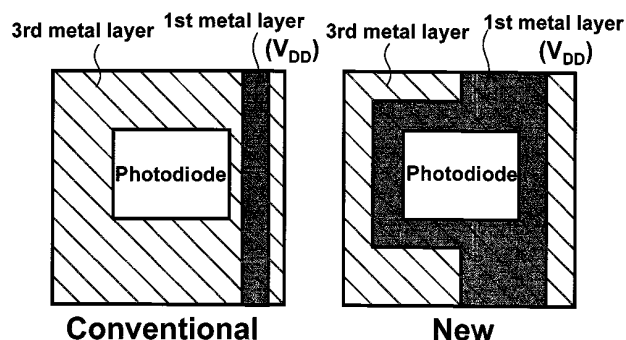


Fig. 12. Schematic pixel plane view of photoshield.

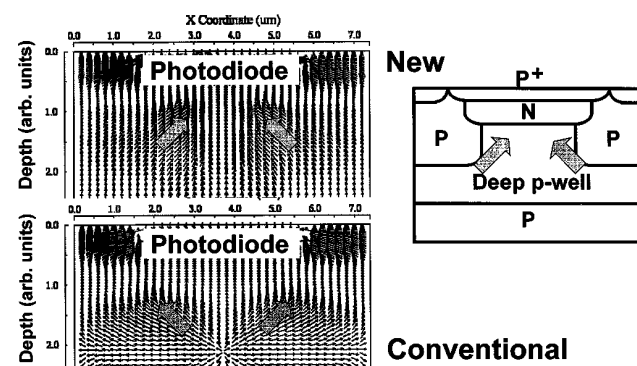


Fig. 13. Simulated electron currents under 700-nm incident light illumination conditions.

D. Deep p-Well and Double-Metal Photoshield for Crosstalk Suppression

Suppressing pixel crosstalk is essential for CMOS image sensors. One effective approach is to prevent obliquely incident light from reaching the outside of the photodiode. We created a double-metal photoshield structure to achieve this purpose. Fig. 12 shows a schematic pixel plane view of the photoshield. The conventional photoshield is formed using only the third metal layer, because the first and second metal layers are used to provide signal and supply lines for the pixel and peripheral circuits. Instead, we used both the first and the third metal layers to form the double-metal photoshield. The first-metal photoshield was formed by using the first metal layer as the V_{DD} line for the pixel. This process does not increase the number of process steps or change the photodiode's aperture as compared with the conventional photodiode.

Another approach for the suppressing crosstalk is to prevent the diffusion of electrons from pixel to pixel. Fig. 13 shows simulated electron currents under 700-nm incident light illumination conditions. In the new photodiode, the electron current vectors are directed toward the center of the photodiode. The deep p-well for the photodiode helps prevent the diffusion of electrons toward neighboring pixels. Electrons generated under the photodiode are effectively gathered by the photodiode. This decreases the crosstalk caused by electron diffusion into adjacent pixels.

We tested the effectiveness of the double-metal photoshield and deep p-well structure in suppressing pixel crosstalk. Fig. 14

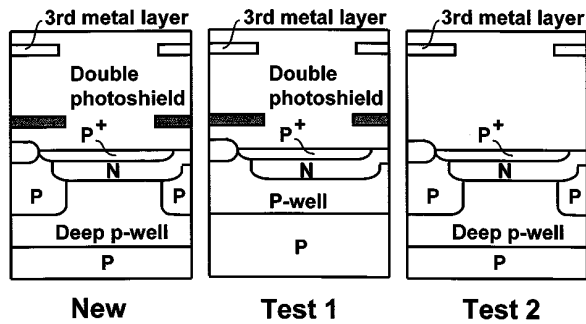


Fig. 14. Cross-sectional views of the test structures.

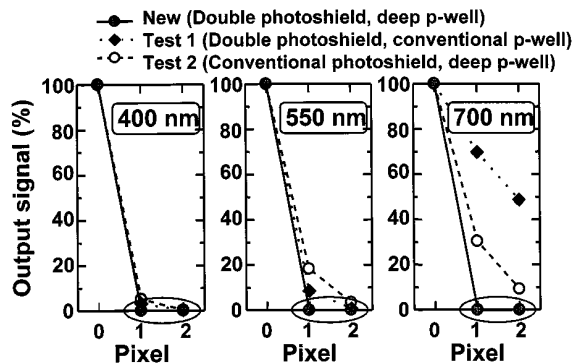


Fig. 15. Pixel crosstalk test results. Pixel 0 is active, while pixels 1 and 2 are OB.

shows cross-sectional views of the test structures. The new structure has both a double-metal photoshield and a deep p-well structure. Test structure 1 has a double-metal photoshield and a conventional p-well, while test structure 2 has a conventional photoshield and a deep p-well. Fig. 15 shows the crosstalk characteristics of these structures. Pixels 0, 1, and 2 are neighbors. Pixel 0 was a currently active pixel, while pixels 1 and 2 were optically black (OB). The OB pixels were formed as same as the active pixels, except the photoshield was fully covered above the photodiode. We regarded the signal in pixel 1 as a crosstalk noise signal from the nearest neighbor active pixel. In the photodiode with our complete new structure, crosstalk never rose above 1% for incident light ranging from 400 to 700 nm.

Comparing the results for test structure 1 and 2 shows that test structure 1 was more effective under 400- and 550-nm incident light conditions, while test structure 2 was more effective under 700-nm incident light conditions. These results show that the double-metal photoshield effectively suppressed crosstalk caused by obliquely incident light, especially for shorter wavelengths, while the deep p-well photodiode structure was more beneficial in suppressing crosstalk caused by longer wavelengths.

We thus obtained a pixel with almost no crosstalk (less than 1%) under incident visible light conditions by using the new structure with the double-metal photoshield and the deep p-well photodiode.

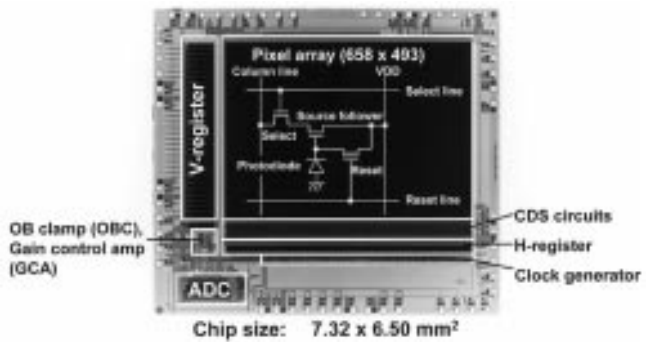


Fig. 16. Chip micrograph of a 1/3-in 330k-pixel CMOS sensor.

TABLE I
DEVICE SPECIFICATIONS AND PERFORMANCE

Optical format	1/3 inch
Pixel size	7.4 μm (H) $\times$ 7.4 μm (V)
Fill factor	20%
Saturation signal	770 mV
Sensitivity	1090 mV/lx·sec (without microlens)
Conversion gain	30 $\mu\text{V}/e$
Dynamic range	51 dB
Dark current	1.5 fA/pixel (25 $^{\circ}\text{C}$)
Power consumption	69 mW
Process	0.35- μm 1-poly 3-metal CMOS
Supply voltage	3.3 V

IV. THE 1/3-in 330K-PIXEL CMOS IMAGE SENSOR

We fabricated a 1/3-in 330k-pixel active-pixel CMOS image sensor by using the new pixel technology, as designed for a 0.35- μm CMOS logic process. A chip micrograph of this image sensor is shown in Fig. 16. The sensor consisted of 658 (H) $\times$ 493 (V) effective pixels, each 7.4- $\mu\text{m}^2/e$. Each pixel consisted of one photodiode and three transistors. The signal charge in the pixel, selected by the vertical and horizontal registers, is read out through a correlated-double-sampling (CDS) circuit and an analog-to-digital converter (ADC).

Table I lists the device specifications and performance. Note that the sensitivity of the pixel was 1090 mV/lx·s, without microlens, and the saturation signal was 770 mV. The dynamic range was 51 dB, measured at analog output. The power consumption was 69 mW, including the ADC, under the condition of 12.27-MHz pixel rate.

Fig. 17 shows a reproduced image obtained by this image sensor. Its resolution is sufficient to provide good image quality, without any serious degradation.

V. SUMMARY

We have developed and demonstrated pixel technology for high photosensitivity and no crosstalk for an active-pixel CMOS image sensor by using a 0.35- μm CMOS logic process. The main features of this pixel technology are a deep p-well photodiode and antireflective film to increase photosensitivity, the use of a depletion-type transistor as the reset transistor to elim-

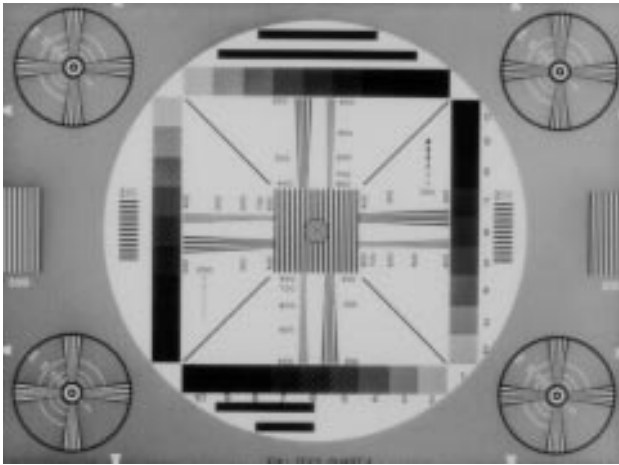


Fig. 17. Reproduced image of a resolution chart.

inate high voltage, and a double-metal photoshield to suppress crosstalk.

A 1/3-in 330k-pixel active-pixel CMOS image sensor was successfully fabricated using this technology. By using a deep p-well photodiode, the sensitivity was 110% higher than that of a conventional photodiode for 550-nm incident light. Also, by forming an antireflective film at the photodiode surface, the sensitivity was improved by 24%. The pixel crosstalk was suppressed to less than 1% throughout the range of visible light by using a double-metal photoshield and a deep p-well photodiode structure.

These results show that this new pixel technology holds promise in developing high-performance CMOS image sensors.

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