P.10 Characterization of CMOS Photodiodes for Imager Application

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Abstract

Image sensor parameters were measured on N-well/P-sub and N^+-diffusion/P-sub photodiodes using two standard CMOS processes. The N-well/P-sub photodiodes demonstrate lower dark current density, higher quantum efficiency, and higher photon-to-voltage conversion gain than the N^+-diffusion/P-sub diodes. The results can be explained by a better-annealed P-N junction, a longer minority carrier diffusion length, and a wider depletion width in the N-well/P-sub photodiode structure.

Introduction

Photodiodes are widely adopted as image sensing elements for CMOS imagers. [1][2] Two photodiode structures, N-well/P-sub diodes and N^+-diffusion/P-sub diodes, are available through modern CMOS processes. The former structure is not often used because it requires a N^+-diffusion/N-well butting junction to electrically connect the N-well region which violates the design rules for typical CMOS processes. However, from an image sensor point of view, a N-well/P-sub photodiode has the potential of providing better image sensor performance. The purpose of this research is to quantitatively compare dark current, quantum efficiency and photon-to-voltage conversion gain for the two photodiode structures.

Device preparation and experiment setup

The geometry of the test structures is shown in Fig. (1). The diode size is 500μm by 500μm to remove geometry effects and provide sufficient signal for measurement accuracy. Devices were fabricated through two standard CMOS processes with minimum feature size of 2.0μm and 0.5μm respectively. The former was a non-silicided process and the latter applied a silicide block mask on active regions.

Photodiode dark current is measured with a HP4140B pA meter. Diodes were probed in a metal shielded box to isolate optical and electrical noise. Each data point is an average of 100 consecutive measurements to reduce random error.

Quantum efficiency (QE) is measured with a pA meter and a ISA TRIAX-180 monochromator as the light source. The output of the monochromator is connected to a bifurcated optical fiber with one end tied to an optical meter and the other end shining on the devices. QE can be calculated from the following equation.

$$QE = \frac{P \cdot e}{(h\nu) \cdot I},$$

where P denotes optical power; e is electron charge; h is Planck's constant, ν is optical frequency and I is measured photocurrent.

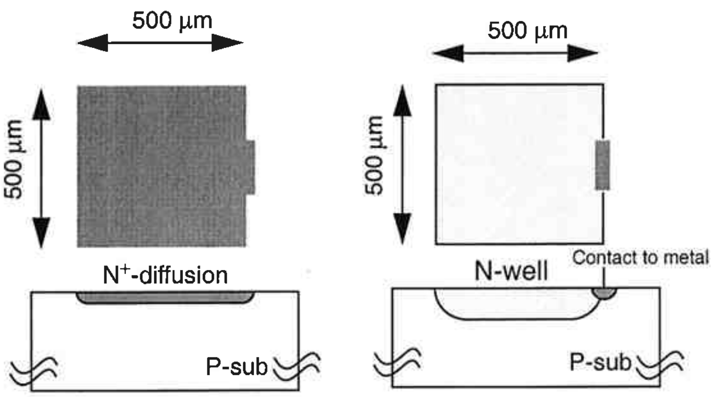

Figure 1. The geometry of the photodiode test structures.

Photon-to-voltage conversion gain is essentially a measurement of junction capacitance. A HP4275 LCR meter is utilized to measure capacitance. All the above measurements are conducted in a metal shielded box at room temperature.

Results and discussion

Dark current has a large impact on image sensor quality at low light conditions since it sets the fundamental lower shot noise limit. The measurement results are shown in Fig. (2). Over 0-5V reverse bias region, the N-well photodiodes present lower dark current density than the N^+-diffusion diodes in both processes. This could be explained by the fact that the lightly-doped N-well/P-sub junction experiences several thermal cycles which anneal out the lattice damage introduced in well-implantation. Unannealed lattice damage will introduce more generation/recombination centers and cause the dark current to rise. A lightly-doped and better-annealed N-well photodiode is a better choice for low light level operation.

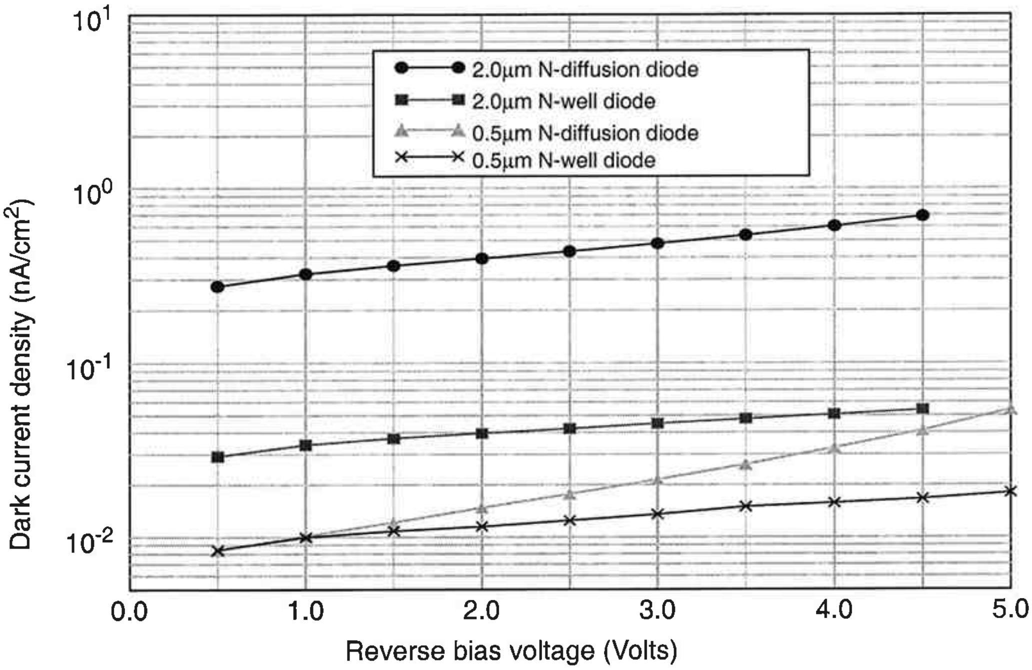

Figure 2. Dark current density versus reverse bias voltage for the photodiodes fabricated with two described processes.

Quantum efficiency is a measurement of the optical-to-electrical conversion factor for a detector at a specific wavelength. The results are shown in Fig. (3). For wavelengths beyond 600nm, both diode structures demonstrate comparable responses. This is because long-wavelength photons generate carriers in the depletion region or deep in the substrate so that the conditions for both structures are similar. The wavy response curve at long wavelengths is due to optical constructive and destructive interference of incident light within passivation layers. However, at short wavelengths, the N-well diodes show better quantum efficiency. The outcome is attributed to a longer minority carrier diffusion length in the N-well. It could be two orders of magnitude longer than the N^+-diffusion in modern processes. Because short-wavelength photons tend to get absorbed and generate carriers near the surface, the carriers generated in the N^+-diffusion layer are more likely to recombine.

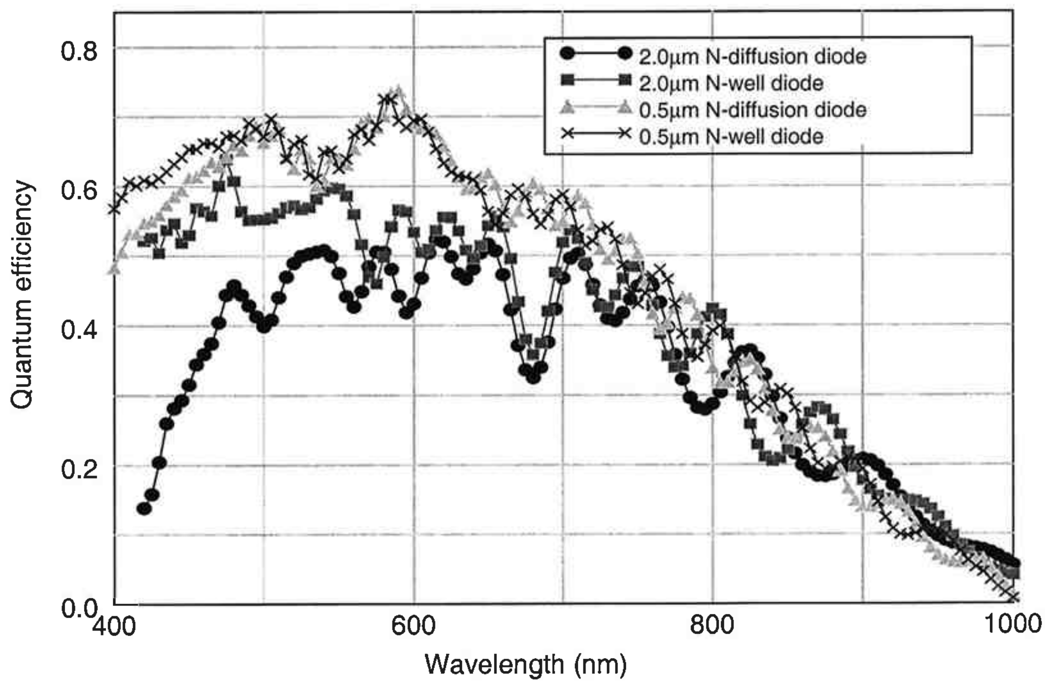

Figure 3. Quantum efficiency measurement of the photodiodes.

Diode capacitance determines the conversion gain of a voltage-sensing active image sensor. As the sensing capacitance gets smaller, the output signal voltage becomes larger. Measurements of the capacitance are shown in Fig. (4). In both processes, the capacitances of the N-well diodes are smaller than the N^+-diffusion diodes. This is simply due to the doping profile difference of the two P-N junctions. The lightly-doped N-well/P-sub junction has a wider depletion width which leads to a smaller capacitance and a larger conversion gain.

The dimensions of the photodiodes used in this research are much larger than typical pixel sizes(~ 10 μmx10μm). It may not be accurate enough to determine pixel sensor parameters by simply multiplying the area scaling factor since the peripheral component is not negligible. However, the described mechanisms also occur at the periphery and the advantage of the N-well photodiode remains. A further study on pixel arrays is currently being performed to allow the extraction of area and peripheral components.

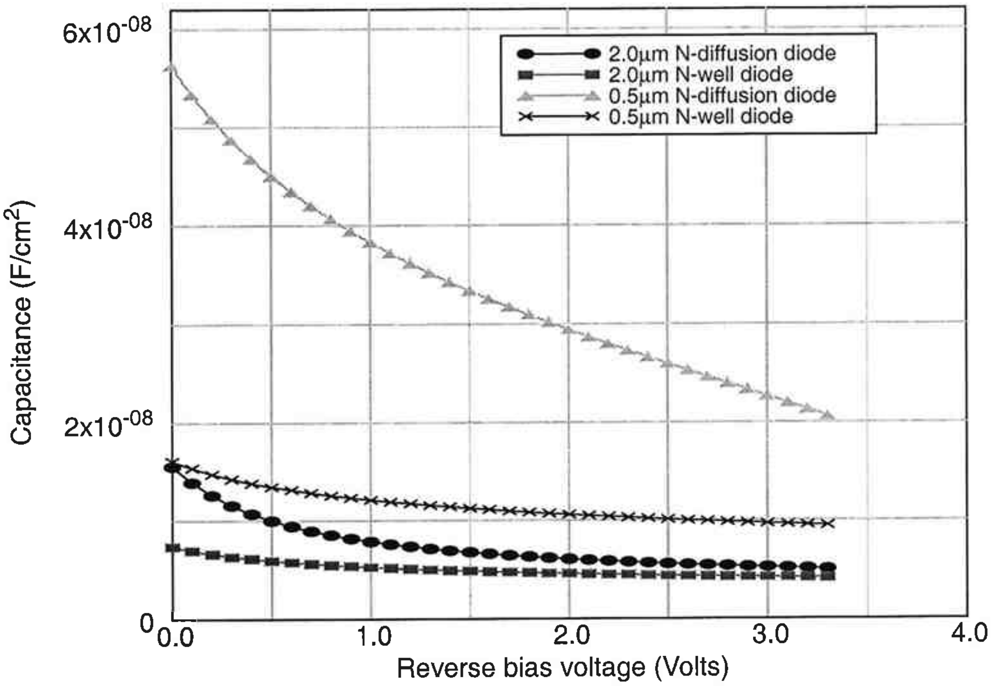

Figure 4. Capacitance measurement of the photodiodes.

Conclusion

Our measurement results demonstrate that the N-well photodiodes have lower dark current density, higher quantum efficiency, and higher conversion gain than the N^+-diffusion diodes on two distinct CMOS processes. A better thermal annealing treatment and lower doping concentration account for the performance enhancement. It is recommended to adopt N-well photodiodes for CMOS imager application.

Reference

[1] E.R.Fossum, "CMOS Image Sensors: Electronic Camera-On-A-Chip," IEEE Tran. on Elec. Dev., pp.1689-1698, Vol.44, No.10, Oct 1997.

[2] W. Yang et al., "An integrated 800x600 CMOS Imaging System," pp.304, ISSCC Digest 1999.