Stanford BICMOS process [2]. Thirteen masks were needed on the front for a twin-well, single-level metal, single-level poly CMOS process implementing the readout circuitry, and three masks on the back for the back-side diode and proper junction termination. The process contained several high-temperature steps (e.g., the well drive-in is 16 h at 1150°C). A combination of the deposition of undoped poly, needed for the transistors on the top side anyway, and a high-dose phosphorus implant (10^{16} cm^{-2} at 100 keV) provided gettering on the back side. A similar step was proposed earlier [3], [4], where an *in situ* phosphorus-doped polysilicon layer was used for gettering at lower temperatures. The leakage current in the p-i-n diodes is about 30 nA/cm² at room temperature for a depletion layer thickness of 300 μm . We believe this is the first time that such a technique has been used successfully in combination with anneals at these high temperatures.

The fabricated array has been fully tested with infrared light as the signal input. Testing is currently underway with ionizing radiation sources. The array performance has verified the high resolution and high sensitivity expected for the new structure.

*The Department of Energy provided financial support under project DE-AC03-83ER40103. University of Hawaii, Dept. of Physics, High Energy Physics Group, Honolulu, HI 96822.

- [1] S. Parker, "A proposed VLSI pixel device for particle detection," *Nucl. Instrum. and Meth.*, vol. A275, pp. 494-516, Mar. 1989.
- [2] Center for Integrated Systems, Stanford University, *The Stanford BICMOS Project*, 1990.
- [3] S. Holland, "Fabrication of detectors and transistors on high-resistivity silicon," *Nucl. Instrum. and Meth.*, vol. A275, pp. 537-541, Mar. 1989.
- [4] —, "An IC compatible detector process," *IEEE Trans. Nucl. Sci.*, vol. 36, pp. 283-289, Feb. 1989.

IIB-8 Tri-Colorimetric Detector in Silicon with One Photodiode—R. F. Wolfenbuttel, E. J. Blaauw, M. R. Wolfenbuttel, and G. de Graaf, Delft University of Technology, Dept. of Electrical Engineering, Laboratory for Electronic Instrumentation, Mekelweg 4, 2628 CD Delft, The Netherlands.

Conventional techniques to fabricate solid-state color imagers are based on the deposition of an array of three different types of dyed polymer filters, each on one of the three, clustered, integrated photodiodes. Combining the photocurrents of the three photodetectors, that constitute one color element, gives the colorimetric information. Although high-density solid-state color imagers have been reported, there are two disadvantages of this technique. First, it is necessary to have three detectors per color element to unambiguously retrieve the color of the impinging light. Secondly, extra fabrication steps are required for the dye deposition. Recently, the properties of the peripheral photoresponse [1] and the effect of bulk depletion [2] have been studied in view of its application in programmable color filters. Vertical depletion greatly affects the long-wavelength response, whereas the peripheral photoresponse can be made pre-eminently effective at short wavelengths. This paper is about a technique that has been developed and implemented in silicon to independently program the long- and the short-wavelength response of a photodiode in order to have a tri-colorimetric response using only one diode without dyed filters by switching between reverse voltages.

A p⁺-n diode is surrounded by a ring-shaped p⁺ layer. The diode is covered by a thermal oxide, a polysilicon layer, and a second oxide layer. The thickness of the thermal oxide is designed to give an optimum short-wavelength transmission of impinging light into

silicon in the peripheral area. The oxide-poly-oxide-silicon multilayer acts as an interference filter with a bandpass transmission in the green-reddish part of the spectrum. This implies that the blue light penetrates mainly in the peripheral area, while the green-red part is absorbed underneath the photodiode. Silicon has a strongly wavelength-dependent penetration depth for light in the visible part of the spectrum, which is due to its indirect bandgap. Short-wavelength light is absorbed close to the surface, while long-wavelength light (red) penetrates deeply in the bulk. Vertical depletion gives an efficient detection of the longer wavelength light. Lateral depletion of the peripheral area strongly reduces the recombination of shallowly generated photocharge at the silicon-oxide interface.

Short-circuiting of the photodiode gives a high efficiency for green light. Applying a high reverse voltage across both the photodiode and the ring-shaped junction gives vertical and lateral depletion and consequently results in an increased contribution of the bulk-absorbed long-wavelength light to the photocurrent. However, a large amount of the peripheral photocharge flows towards the ring-shaped junction. Short-circuiting of the ring while increasing the reverse voltage across the photodiode gives, in addition, an increase in the contribution to the peripheral photocurrent and thus leads to an improvement of the short-wavelength response.

A switching sequence has been designed to identify the three primary colors. Short-circuiting of both junctions gives a high sensitivity to green light, as this light is absorbed close to the junction. Red light penetrates deeper and charge carriers generated by blue light in the peripheral area, recombine near the surface, unless it is depleted. This mechanism is limited by the surface accumulation, which is due to the oxide charge and the interface traps. Green, green + blue, and green + blue + red is detected when switching to $V_1 = V_2 = 0$, $V_1 = V_2 = V_{\max 1}$, and $V_1 = V_{\max 2}$, $V_2 = 0$, respectively, with $V_{\max 2} > V_{\max 1}$. The substrate voltage is controlled to deplete the remainder of the epitaxial layer. A practical color element has been fabricated using this concept with 10- μm spacing between photodiode and ring and a response. A problem is the reachthrough. A color imager can be constructed by replacing the ring-shaped junction by photodiodes in an array. The peripheral area between the diodes is shared among the surrounding diodes, whose switching sequences are complementary.

- [1] R. F. Wolfenbuttel, "Photodiodes in silicon with an electrically-programmable UV response," *Sensors and Actuators*, vol. A21-A23, pp. 559-563, 1990.
- [2] —, "Color filters integrated with the detector in silicon," *IEEE Electron Device Lett.*, vol. EDL-8, no. 1, pp. 13-15, 1987.

IIIA-1 Low Series Resistance Continuously Graded Mirror Multiple Quantum-Well Vertical-Cavity Surface-Emitting Lasers Grown by MOCVD—Ping Zhou, Julian Cheng, C. F. Schaus, S. Z. Sun, D. Kopchik, C. Hains, Wei Hsin, Chien-hua Chen, University of New Mexico, Center for High Technology Materials, Albuquerque, NM 87131; D. R. Myers, G. A. Vawter, G. R. Olbright, and R. P. Bryan, Sandia National Laboratories, Albuquerque, NM 87185.

We report the first demonstration of room-temperature, CW operation of GaAs/AlGaAs multiple quantum-well vertical-cavity surface-emitting lasers (VCSEL's) with continuously graded mirror layers grown by MOCVD. Continuous grading of the heterojunction interfaces in the heavily doped p-type distributed Bragg reflector (DBR) layers significantly reduced the diode resistance and self-heating, thus leading to higher power efficiencies, a wider CW current range, and a light output that is comparable to the MBE