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Fully tileable photodiode matrix for medical imaging by using through-wafer interconnects

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Abstract

This paper presents a technology for a fully tileable two-dimensional (2D) photodiode matrix for medical imaging, specifically X-ray computed tomography (CT). A key trend in the CT industry is to build machines with larger area detector to speed up the measurements and to avoid image blurring due to patient movement during scanning. In current CT detector constructions, a major limiting factor in providing more detector coverage is the need to read out the signals from the individual photo-detector elements of the detector array through lines along the surface facing the radiation source and wire bonds down to a substrate or to an electronics chip. Using this method, there is a physical limitation on the size of a photo-detector array that may be manufactured. A photo-detector with the possibility of expansion in all directions is known as a 'tileable' detector. A technology of integrating through-wafer interconnects (TWIs) with traditional front illuminated photodiodes is introduced. Photocurrent can be read out from back side of the photodiode chip through interconnects, giving possibility of constructing arbitrarily large area of photo-detector for CT machine. Results of a sample 2D demonstrator detector array are presented showing that the requirements of modern CT systems can be met.

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Keywords: Computed tomography; Tileability; Through-wafer interconnect

1. Introduction

In a typical computed tomography (CT) system, an X-ray source and a two-dimensional (2D) radiation detector array are assembled on a mechanical support structure, known as a gantry. In use, the gantry is rotated around an object to be imaged in order to collect X-ray attenuation data from a constantly changing angle with respect to the object. The plane of the gantry rotation is known as an imaging plane, and it is typically defined to be the x–y plane of the coordinate system in a CT system. In addition, the gantry (or more typically the object) is moved slowly along the z-axis of the system in order to collect X-ray attenuation data for a required length of the object.

The radiation detectors of current state of the art CT systems consist of a 2D array of rare earth metal-based scintillators and a corresponding 2D array of silicon photodiodes. Scintillator materials convert X-ray photons into visible light photons, which are then further detected by the photodiodes. Both the scintillator crystals and the photodiodes are manufactured in 2D arrays, which are then optically coupled to one another during detector manufacturing.

In order to present 3-D image data useful for the user of the CT system, complex reconstruction algorithms and software are utilised after or during data collection.

In CT imaging systems, the size of the detector in the imaging plane is increased by placing individual detector arrays adjacent to each other. A key trend in the CT industry is to build CT machines with more detector elements in the z-axis direction in order to collect more X-ray attenuation data for each gantry rotation and therefore to speed up the measurements; to improve the accuracy of the measurements; and to decrease patient radiation dose in medical applications. An increase in the

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number of detector elements has advantages in various imaging applications.

A photo-detector with the possibility of expansion in all directions is known as a 'tileable' detector. In order to provide a tileable detector, it is necessary to make the electrical connection to each photo-detector without wiring the photo-detectors to the bonding pads on chip edge. If this can be achieved, there is no limitation to the growth of the photo-detector array and consequently the number of photo-detector elements.

This paper presents a technology for a fully tileable 2D photodiode detector matrix for medical imaging, specifically X-ray CT. A technology of integrating through-wafer interconnects (TWIs) with traditional front illuminated photodiodes is introduced. Front side of the device is defined as the side where the light detecting diodes have been processed. Front illumination thus means that the X-rays and the optical photons from the scintillator are arriving to the photo-detector on the same side where the diodes are processed. The purpose of TWIs is to access signals from the back side of the device. Photocurrent can then be read out from back side of the photodiode chip through interconnects, giving possibility of assembling individual array components together into two dimensions without the packaging gap normally required by wire bonding technology. Results of a sample 2D demonstrator detector array assembled onto a module substrate are presented showing that all parameters can meet the requirements of modern CT systems.

2. Device design and manufacturing

A test photodiode chip with 16×16 active elements and corresponding amount of TWIs was designed. The chip size is approximately $20\,\mathrm{mm} \times 20\,\mathrm{mm}$ with approximately 1.25 mm photodiode pitch. Active area of each photodiode is approximately $1\,\mathrm{mm}^2$. The photodiodes were designed and optimized for application with no bias voltage, that is, to be virtually grounded through the readout chain. On the back side of the chips, signal lines from the vias were redistributed to round $\varnothing 500\,\mu\mathrm{m}$ contact pads with soldering compatible under bump metallization (UBM). Additional $200\,\mu\mathrm{m} \times 400\,\mu\mathrm{m}$ contact pads were also designed on the front surface for the TWI probing.

A test FR4-Rogers substrate was designed to carry two such photodiode chips, with a connector on the opposite side of the substrate, resulting into a 16×32 pixel module that could be used in a 32 slice CT machine.

N-type silicon wafers were first prepared with TWIs [1]. The process included DRIE/ICP Bosch method [2] to etch $\varnothing 40\,\mu\mathrm{m}$, $>400\,\mu\mathrm{m}$ deep cavities to the wafer, isolation by thermal oxidation of the cavities, filling the cavities by in situ p+ doped poly-Si material [3], and accomplishing TWIs by grinding and chemical mechanical polishing (CMP).

Photodiodes were then processed on these wafers now carrying TWIs. Photodiode process included normal oxidation, lithography, ion implantation and drive in stages. p-Type implantations were used to form the active areas (anodes) on front side and n+ implantations were processed on the back side for proper bulk (cathode) contact for each chip. Contacts were opened to each active area, on both ends of the TWIs, and to n+ cathode implantations. Aluminium metallization was patterned to connect the diodes to the front ends of the TWIs and to have contacts to the back ends of the TWIs and to the cathode implantations. Finally, soldering compatible UBM was processed on the contact pads on the back surface of the wafer and the individual chips were diced out.

After testing at chip level, solder bumps were processed on the chips. Thereafter the chips were assembled on the test substrates by standard surface mount technology. The alignment of the pick and place process was allowed to have quite relaxed tolerance due to the fact that the chips entered into their final positions during the reflow process by the self-centering forces of the solder.

3. Testing methods

The chips were tested before assembly on a Karl Süss probe station using a specifically designed probe card with 32 probes for anodes and two probes for cathodes, and a relay card connecting one channel at a time to measure the electrical characteristics. HP 4156A Parameter Analyzer was used for various current vs. voltage measurements and Keithley 590 CV analyzer for capacitance measurements. Forward bias current characteristics, reverse bias current characteristics (= dark or leakage current) and capacitance were measured from each photodiode.

The above characteristics were measured both from front and back side of the chip to analyze the possible differences caused by the TWIs. Some of the measurements were also performed by intentionally breaking the connection of the diode to its TWI. Properties of the TWIs alone were measured by placing the chip on a conductive chuck grounding the back side ends of the TWIs, and probing from the front side.

After assembly, the modules carrying two 16×16 pixel chips were tested on a specific test bench in a dark cabinet, having a counterpart for the connector on the module, a relay board to connect one channel at a time to measurement equipment while grounding the neighbouring channels, and a relatively uniform white light source. Using a Keithley 6517A Electrometer, the dark current measurements were repeated at 10 mV reverse bias from each pixel and the light current of each photodiode pixel was measured to verify the functionality of the module. It should be noted here that this test setup is built for CT detector volume production testing at Detection Technology, Inc. only to verify functionality, not to really evaluate uniformity of signal levels from pixel to pixel.

The spectral response of the device was measured in an optical test bench using a mercury lamp and a monochromator to scan over spectral range of 320–1040 nm.

Spectral response was measured from a specific test diode processed on same wafers, but larger than the individual pixels in the 16×16 pixel array. A larger diode was used to avoid measurement errors easily caused by part of the light source beam falling outside the photodiode area.

Since the modules were designed to meet the requirements of a possible real CT machine, the mechanical properties of the modules were also tested. A specific concern is the front surface flatness of the photodiodes and their possible height differences. Since a scintillator will be assembled very close (within few tens of μm) to the photodiode surface, possibly extending over several individual photodiode chips, and uniform optical coupling properties are required, the flatness and height differences of the diodes must be within certain limits. Also, the two chips must be very precisely in their designed positions to allow for good image reconstruction, and assembly into a gantry. Mechanical measurements were performed using a high precision measurement microscope.

4. Measurement results

The properties of the TWIs have been reported elsewhere [1], and are only summarized here. Resistance of 220 Ω was achieved with relatively even distribution over wafer. Total capacitance of a TWI, including the front side probing pad and back side contact pad was 22 pF at 100 kHz testing frequency and 0 V bias voltage. Since the plate capacitance of the contact pads can be calculated fairly precisely when the oxide thicknesses are known, it could be concluded that the TWIs alone had about 3 pF capacitance.

The *I–V* measurements of the photodiode chips showed that the individual diodes had properties essentially equivalent to the same size of photodiodes processed conventionally with front side contacts, except that the variation in dark current was somewhat larger. Dark current map of a photodiode chip is shown in Fig. 1. Dark current was typically in 2 pA range at 10 mV reverse bias. The breakdown tolerance was good showing less than 50 pA dark current at 5 V reverse bias. Terminal capacitance of the diodes, including the diode itself, the test and contact pads, and the TWI was typically 30 pF, which is slightly larger than required. However, very straightforward capacitance reduction possibilities include removal of the front side test pad and optimization of back side contact pad size and shape for future product designs.

Test results of the assembled module confirmed that the assembly method was capable of producing functional modules. The dark currents remained essentially unchanged over the pick and place and solder reflow processing. The light response distribution also showed that pixels having normal diode properties under *I–V* testing in probe station also produced quite equivalent light current (= signal) under uniform white light testing. Light response map is shown in Fig. 2. Height differences seen in the map can mainly be attributed to the inaccuracies in the test setup, which is designed for high-speed verification of functionality, not for precision measurement of uniformity. Some of the higher light current levels, however, are caused by leakage through some faulty TWIs.

Spectral response measurements indicated that spectral response was essentially equivalent to same size of photodiodes processed conventionally with front side contacts. This was quite an expected result at this point since all other diode properties had already been shown to not having suffered from the TWI processing.

Mechanical measurements indicated that positional tolerances relevant for CT detector module design could be achieved. Also, measurement of the height values of photodiode surface at different points across the devices indicated that 33 μm peak-to-peak deviation from flatness was achieved.

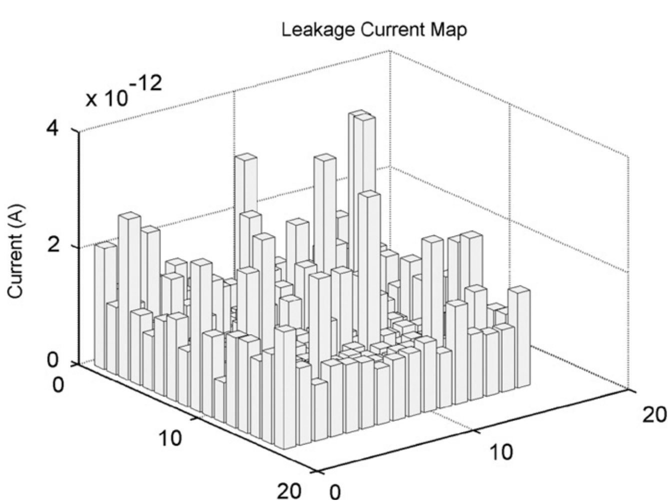

Fig. 1. Leakage current map of a 16×16 pixel photodiode array at 10 mV reverse bias.

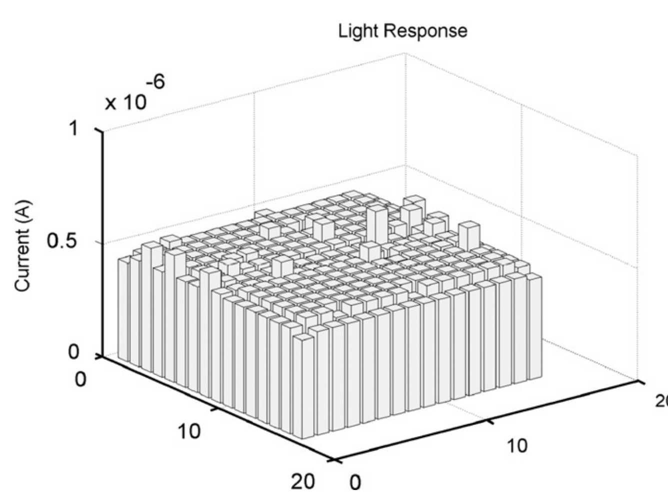

Fig. 2. Light current distribution of a 16×16 pixel photodiode assembled on a substrate.

5. Conclusions

The technology for a fully tileable 2D photodiode detector matrix presented in this paper has been shown to provide characteristics feasible for medical imaging, specifically X-ray CT. Photocurrent can be read out from back side of the photodiode chip through interconnects, giving possibility of constructing arbitrarily large area of photo-detector for CT machines. Results of sample demonstrator detector array were presented showing that the requirements of modern CT systems can be met.

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