

the Space Shuttle Orbiters (see Figure 1). The system may be easily adapted to other applications that involve similar coordinate-measuring requirements. Examples of such applications include manufacturing, construction, preliminary approximate land surveying, and aerial surveying.

For some applications with rectangular symmetry, it is feasible and desirable to attach a target composed of black and white squares to an object of interest (see Figure 2). For other situations,

where circular symmetry is more desirable, circular targets also can be created. Such a target can readily be generated and modified by use of commercially available software and printed by use of a standard office printer. All three relative coordinates ( $x$ ,  $y$ , and  $z$ ) of each target can be determined by processing the video image of the target. Because of the unique design of corresponding image-processing filters and targets, the vision-based position-measurement system is extremely

robust and tolerant of widely varying fields of view, lighting conditions, and varying background imagery.

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## N-Type $\delta$ Doping of High-Purity Silicon Imaging Arrays

Success depends on details of a low-temperature MBE process.

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A process for n-type (electron-donor) delta ( $\delta$ ) doping has shown promise as a means of modifying back-illuminated image detectors made from n-doped high-purity silicon to enable them to detect high-energy photons (ultraviolet and x-rays) and low-energy charged particles (electrons and ions). This process is applicable to imaging detectors of several types, including charge-coupled devices, hybrid devices, and complementary metal oxide/semiconductor detector arrays.

Delta doping is so named because its density-vs.-depth characteristic is reminiscent of the Dirac  $\delta$  function (impulse function): the dopant is highly concentrated in a very thin layer. Preferably, the dopant is concentrated in one or at most two atomic layers in a crystal plane and, therefore,  $\delta$  doping is also known as atomic-plane doping. The use of  $\delta$  doping to enable detection of high-energy photons and low-energy particles was reported in several prior *NASA Tech Briefs* articles. As described in more detail in those articles, the main benefit afforded by  $\delta$  doping of a back-illuminated silicon detector is to eliminate a "dead" layer at the back surface of the silicon wherein high-energy photons and low-energy particles are absorbed without detection. An additional benefit is that the delta-doped layer can serve as a back-side electrical contact.

Delta doping of p-type silicon detectors is well established. The development of the present process addresses concerns specific to the  $\delta$  doping of high-purity silicon detectors, which are typically n-type. The present process involves relatively low temperatures, is fully compatible with other processes used to fabricate the detectors, and does not entail interruption of those processes. Indeed, this process can be the last stage in the fabrication of an imaging detector that has, in all other respects, already been fully processed, including metallized.

This process includes molecular-beam epitaxy (MBE) for deposition of three layers, including metallization. The success of the process depends on accurate temperature control, surface treatment, growth of high-quality crystalline silicon, and precise control of thicknesses of layers. MBE affords the necessary nanometer-scale control of the placement of atoms for delta doping.

More specifically, the process consists of MBE deposition of a thin silicon buffer layer, the n-type  $\delta$  doping layer, and a thin silicon cap layer. The n dopant selected for initial experiments was antimony, but other n dopants as (phosphorus or arsenic) could be used. All n-type dopants in silicon tend to

surface-segregate during growth, leading to a broadened dopant-concentration-versus-depth profile. In order to keep the profile as narrow as possible, the substrate temperature is held below 300 °C during deposition of the silicon cap layer onto the antimony delta layer. The deposition of silicon includes a silicon-surface-preparation step, involving H-termination, that enables the growth of high-quality crystalline silicon at the relatively low temperature with close to full electrical activation of donors in the surface layer.

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