USING A DELTA-DOPED CCD TO DETERMINE THE ENERGY OF A LOW-ENERGY PARTICLE

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ABSTRACT

The back surface of a thinned charged-coupled device (CCD) is treated to eliminate the backside potential well that appears in a conventional thinned CCD during backside illumination. The backside of the CCD includes a delta layer of high-concentration dopant confined to less than one monolayer of the crystal semiconductor. The thinned, delta-doped CCD is used to determine the energy of a very low-energy particle that penetrates less than 1.0 nm into the CCD, such as a proton having energy less than 10 keV.

8 Claims, 6 Drawing Sheets
FIG. 3

1. Obtain conventional CCD

2. Clean back surface via H-termination

3. Create vacuum of $8 \times 10^{-8}$ Pascal

4. Heat CCD to at least 200°C

5. Heat CCD to at least 370°C

6. Deposit 1nm of heavily doped Si

7. Deposit p+delta layer

8. Deposit 1.5nm cap layer of undoped Si

9. Form thin oxide on back surface
FIG. 4
FIND ARRAY MEAN SIGNAL AND STANDARD DEVIATION

READ SIGNAL FROM ONE PIXEL

NO

PIXEL > 3 STD. DEVIATIONS?

YES

NO

PIXELS > NEIGHBORS?

YES

DESIGNATE PIXEL AS A HIT

NO

SUM VALUE OF PIXEL WITH VALUES OF NEIGHBORS

DIVIDE TO BY TOTAL OF PIXEL VALUES

YES

PIXELS REMAINING?

NO

DESIGNATE PIXEL AS "NO HIT"

STOP

FIG. 5
MEASURE TOTAL CHARGE FROM EACH HIT PIXEL AND ITS NEIGHBORS

FETCH CONVERSION FACTOR

DETERMINE PARTICLE ENERGY

FIG. 6

FIG. 7
A conductive gate 16 is formed on the front surface by serial measurement of the charge collected in each pixel provisions of Public Law 96-517 (35 USC 202) in which the energy of the particles penetrating the semiconductor 12 near the semiconductor-oxide surface 24. Depending on whether the semiconductor is p-type or n-type, the electrons or the holes migrate toward the back surface 20 of the semiconductor substrate 12. In operation, the conductive gate 16 is biased with respect to the back surface 20 of the semiconductor substrate 12 by a voltage supply V. As photons or particles strike the device 10 through its back surface, electron-hole pairs form in the substrate core 12. Depending on whether the semiconductor is p-type or n-type, the electrons or the holes migrate toward the semiconductor-oxide surface 24, where they accumulate in a “collection well” 26 (FIG. 1B) that develops in the semiconductor substrate 12 a given distance below the insulating layer 14. Incident energy from photons or particles is converted into charge in the semiconductor core, and the charge accumulates in the Collection of particles penetrating the semiconductor 12 during the integration period. The energy of the particles penetrating the semiconductor 12 during the integration period. The efficiency of the conversion of energy to charge depends on the energy-dependent interacting of photons or particles in the CCD structure. Therefore, different CCD structures can have markedly different efficiencies. The CCD 10 generates an output signal by serial measurement of the charge collected in each pixel during the integration period.

FIG. 1A is a partial cross-sectional view of a conventional thinned CCD. FIG. 1B shows the electric potential well that forms in a conventional thinned CCD.
FIG. 2 is a partial cross-sectional view of a thinned CCD having a backside delta layer.

FIG. 3 is a simplified flow chart of a method for forming the backside delta layer.

FIG. 4 is a schematic diagram of a low-energy particle detection system including a delta-doped CCD.

FIG. 5 is a flow chart of a process for detecting individual particles, such as low-energy protons, with a delta-doped CCD array.

FIG. 6 is a graph illustrating the relationship between the energy of an incident proton and the number of electrons collected in the delta-doped CCD.

FIG. 7 is a flow chart of a process for determining the energy of a particle detected by a delta-doped CCD.

The figures are exemplary and are not drawn to scale.

DETAILED DESCRIPTION

FIG. 2 shows the general structure of a “delta-doped,” thinned CCD capable of detecting particles having penetration depths into silicon as low as 0.5 mm to 1.0 mm. Like a conventional thinned CCD, the delta-doped CCD includes a lightly doped semiconductor core 52 with an insulating material 54 formed on its front surface 56. An oppositely charged doping layer 55 may be implanted on the front surface 57 of the semiconductor core 52 to create a “buried channel” CCD. The thinned CCD also includes an array of conductive gates 58 on the front surface 60 of the insulating layer 54.

The back surface 62 of the semiconductor substrate 52 includes several layers not found on a conventional thinned CCD. The innermost layer 64 is an epilayer of heavily doped semiconductor material, typically of the same type forming the semiconductor core 52. The middle layer is a very thin delta epilayer 66 of dopant material having a very high surface concentration. The outer layer is a protective layer 68 of nominally undoped semiconductor material that prevents the delta layer 66 from oxidizing. The protective layer 68 may be treated, as described below, to form a protective oxide on its exposed surface.

In one implementation, the delta-doped, thinned CCD includes a 15 μm silicon core 52, lightly doped with boron atoms at a concentration of approximately 10^{14} B/cm^2. The silicon core has an n-type implantation layer 55 at its front surface 57, onto which an insulating layer 54 of silicon oxide is deposited. The inner layer 64 on the back surface 62 of the CCD is a 1 nm layer of heavily doped silicon having a doping level of approximately 4x10^{20} B/cm^2. The delta layer 66 consists of a very high concentration of boron atoms, with a surface density of on the order of 2x10^{14} B/cm^2, deposited by molecular beam epitaxy (MBE) and confined to less than one monolayer, e.g., 1/3 monolayer, of the silicon crystal. The outer layer 68 is a 1.5 nm layer of nominally undoped silicon, onto which a thin protective layer of silicon oxide is allowed to form.

FIG. 3 is a simplified flow chart for a process that may be used to form a delta-doped CCD. The process is described in more detail in U.S. Pat. No. 5,376,810, issued on Dec. 27, 1994, and incorporated in this application by reference. The process begins with the acquisition of a conventional thinned CCD, such as a fully processed, unmounted, and backside-thinned Reticon CCD (512x512 pixels, 27 μm/pixel) marketed by EG&G (step 100). The back surface of the CCD is cleaned and the native oxide layer is removed by conducting a conventional H-termination cleaning process (step 102). Cleaning the backside-thinned CCD in this manner exposes the device’s semiconductor core. The CCD then is placed into a vacuum chamber and subjected to a vacuum on the order of 2x10^{-10} torr (step 104). In the chamber, the CCD is heated first to a temperature of approximately 200° C. (step 106) and then to a temperature of at least 370° C. (step 108).

When the CCD reaches the appropriate temperature, the heavily doped semiconductor epilayer is deposited onto the back surface of the CCD using a conventional molecular beam epitaxy (MBE) technique (step 110). The delta layer then is formed via MBE by interrupting the semiconductor flux and allowing dopant atoms to accumulate on the surface (step 112). When the semiconductor flux resumes, the dopant profile contains a sharp peak, resembling the mathematical delta function. The protective layer of nominally undoped semiconductor material then is deposited onto the delta layer (step 114). For a silicon CCD, a thin oxide layer (~20 Å) may be formed on the exposed surface of the protective layer by exposing the CCD to steam from boiling deionized water for several minutes.

In operation, the heavily doped semiconductor layer and the delta layer act to virtually eliminate the potential well that otherwise would form in the semiconductor substrate of a thinned CCD. As a result, the “dead layer” at the back surface of the substrate is eliminated, and charge generated by particles is collected at the semiconductor’s front surface instead of at the potential well. As a result, efficiency is markedly improved in the delta-doped CCD structure. Deposition of the delta layer through molecular beam epitaxy, as described above, provides more effective and more permanent protection against potential wells than conventional backside treating processes. Moreover, the delta-doped structure is more efficient than the ion implanted structure, because the delta-doped CCD structure contains an atomically abrupt, high-concentration dopant profile and does not contain crystal lattice damage generally associated with ion implantation.

FIG. 4 shows a low-energy particle detection and imaging system that employs a delta-doped CCD 152. The system 150 can be used, e.g., as a plasma detector to monitor solar wind. The delta-doped CCD 152 is positioned so that low-energy particles 154 penetrate the backside surface 156 of the CCD 152. With a conventional backside-treated CCD, charged particles must penetrate at least an effective amount, e.g., 50–100 nm into the semiconductor to overcome the backside potential well. With a delta-doped CCD, however, a particle must penetrate only 0.5 nm to 1.0 nm beyond the protective oxide film to create enough charge in the CCD for detection. At these small penetration depths, the delta-doped CCD can detect electrons having energies below 1 keV and as low as 50 eV and can detect protons having energies below 10 keV and as low as 1.2 keV.

The particle detection system 150 includes no obstructions or elements through which the low-energy particles 154 must pass to reach the CCD 152. Unlike conventional CCD-based particle detection systems, the delta-doped system 150 does not require, and should not include, any particle acceleration or amplification devices, such as microchannel plates. Instead, low-energy particles strike the back surface 155 of the delta-doped CCD 152 directly.

The CCD 152 collects charge over a given collection interval, the length of which is determined by the particular detection application. At the end of the collection interval, a processing device, such as a digital camera, measures the charge at each pixel via a serial read-out process.

The camera 156 includes an analog-to-digital converter (ADC) 158, which converts the analog output of the CCD
into digital data. A processor 160 uses the data, e.g., to determine how many low-energy particles were received by the CCD 152 and to create an image of the particle flux. The processor may store the results in an electronic storage device 162 and display the image on a display device 164, such as a CRT monitor.

In many applications, the particle detection system is used to detect particles with enough energy to generate more than one electron in the CCD. In a backside-illuminated device, electrons generated by the incoming particle must diffuse from the backside to the pixel to be detected. If the diffusion distance is comparable to or is larger than the pixel size, some electrons might diffuse into neighboring pixels. In some implementations, the particle detection system accounts for this type of charge-splitting among pixels. FIG. 5 is a flow chart of one method for doing so.

In applying the method of FIG. 5, the particle detection system first processes the incoming signals from the CCD array to determine the mean signal value and the corresponding standard deviation for the individual pixels in the array (step 200). The system then determines which, if any, pixels were "hit" by a particle. The system does so by comparing each pixel’s value to the mean value (step 202) and to the values of all laterally and diagonally adjacent ("neighboring") pixels (step 204). If the value of the pixel of interest is not greater than the values of all neighboring pixels or does not exceed the mean value by more than a given number of standard deviations, the system determines that no particle has struck the pixel (step 206). If, on the other hand, the pixel has a value greater than the values of its neighboring pixels and sufficiently greater than the mean value, the system determines that the pixel has been hit by a particle (step 208). In other words, when a particle strikes more than one pixel, the detection system treats a pixel as having been hit by that particle only if the pixel produces more charge than its neighboring pixels and sufficiently more charge than the average pixel.

The system then processes the data from each hit pixel to account for charge-splitting among the hit pixel and its neighboring pixels. In many applications, the system does this by averaging the value of the hit pixel with the values of its neighbors, e.g., by summing the values of the hit pixel and its neighbors (step 212) and then dividing the sum by the number of pixels contributing to the sum (step 214).

In addition to the detection and imaging of charged particles, the particle detection system can be used to determine the energy of a particle striking the CCD array. Energy determination relies on an understanding of the relationship between the energy of a particle striking a CCD and the number of electrons collected in the CCD as a result of the particle’s penetration. Because the delta-doped CCD essentially eliminates the backside potential well associated with other types of CCDs, the delta-doped CCD collects enough charge to determine the energy levels of incoming particles, including protons having energy levels as low as 1.2 keV. Energy determination is enhanced by CCD fabrication techniques that reduce the amount of unwanted charge, or noise, collected in the CCD. Total depletion of electrons or holes at the surfaces of the semiconductor core is one such technique.

FIG. 6 illustrates, for a sample delta-doped CCD, the relationship between the energy of an incident proton and the number of electrons collected by the CCD after the proton strikes the CCD. The plot in FIG. 6 was created by measuring the collected charge in a controlled setting over the course of many "hits" by protons having known energies, and by calculating the mean and standard deviation of collected charge vs. proton energy. The standard deviation is represented by the error bars surrounding each point on the plot.

The plot shows a roughly linear relationship between collected charge and proton energy. In the sample CCD, approximately 69 electrons were collected for each 1 keV of energy possessed by the incident proton. Theoretically, a 1 keV proton produces approximately 277 electrons in a CCD. However, while the exact number of electrons produced per particle is under dispute, a detailed calibration of the delta-doped CCD provides information indicating the incoming particle energy.

The linear relationship is used to calculate a conversion factor that is stored in the particle detection system, e.g., in the storage device 162 of FIG. 4. The particle detection system uses the conversion factor, as described below, to determine the energy of each incident particle from the data contained in the signals produced by the CCD array.

FIG. 7 is a flow chart of a process for determining the energy of an individual particle. The particle detection system first identifies each "hit" pixel, as described above, and measures the total charge collected in the hit pixel and its neighboring pixels (step 250). The system then reads the conversion factor from the storage device (step 252) and divides the measured value of collected charge by the conversion factor to determine the energy of the incident particle (step 254). The system stores the result for future access and/or displays the result visually to a user.

The invention is not limited to the implementations described above. Semiconductor and dopant materials other than silicon and boron may be used, and the materials may be used in concentrations other than those suggested above. For example, the CCD may include an n-type semiconductor with an n-type delta layer. Layer thicknesses and layer structures also may differ from those described above. Moreover, other crystal growth processes and temperatures may be used to produce delta-doped CCDS. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1. A method for use in determining the energy of a low-energy particle, the method comprising:
   - exposing the back surface of a backside-thinned, delta-doped CCD to the low-energy particle,
   - measuring an amount of electric charge collected in the CCD as a result of the penetration of the low-energy particle through the back surface of the CCD, and
   - applying a conversion factor to the measured charge to calculate the energy of the low-energy particle,
   wherein the low-energy particle is a proton having energy between approximately 10.0 KeV and 1.2 keV.

2. The method of claim 1, wherein the low-energy particle penetrates no more than approximately 1 nm into the CCD.

3. The method of claim 1, wherein the low-energy particle penetrates no more than approximately 0.5 nm into the CCD.

4. The method of claim 1, further comprising calculating the conversion factor by measuring an amount of charge collected as a result of the penetration of a particle having a known energy.
5. An apparatus for use in determining the energy of a low-energy particle comprising:
   a backside-thinned, delta-doped CCD having a back surface through which the low-energy particle penetrates, and
circuitry configured to:
   measure an amount of electric charge collected in the CCD as a result of the penetration of the low-energy particle, and
apply a conversion factor to the measured charge to calculate the energy of the low-energy particle,

6. The apparatus of claim 5, wherein the particle penetrates no more than approximately 0.5 nm into the CCD.
7. The apparatus of claim 5, wherein the particle penetrates no more than approximately 1 nm into the CCD.
8. The apparatus of claim 5, wherein the circuitry also is configured to calculate the conversion factor by measuring an amount of charge collected as a result of the penetration of a particle having a known energy.