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Determination of the Depletion Depth of the Deep Depletion Charge-Coupled Devices

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Abstract - A 3-D numerical simulation of a buried-channel CCD (Charge Coupled Device) with a deep depletion has been performed to investigate its electrical and physical behaviors. Results are presented for a deep depletion CCD (EEV CCD12; JET-X CCD) fabricated on a high-resistivity (1.5 *kΩ-cm*) 65 *μm* thick epi-layer, on a 550 μm thick p^+ substrate, which is optimized for X-ray detection. Accurate predictions of the Potential minimum and barrier height of a CCD Pixel as a function of mobile electrons are found to give good charge transfer. The depletion depth approximation as a function of gate and substrate bias voltage provided average errors of less than 6%, compared with the results estimated from X-ray detection efficiency measurements. The result obtained from the transient simulation of signal charge movement is also presented based on 3-Dimensional analysis.

Keywords: charge coupled device, charge transfer, deep depletion, depletion depth, 3-D numerical simulation

1. Introduction

Charge-coupled devices play an important role for Astronomical imaging in orbiting X-ray telescopes [1, 2]. Optical properties of a CCD are determined by the absorption mechanism of the incident radiation into the silicon. The diffused electron clouds are formed by Xray photons interacting within the undepleted bulk of silicon beneath the depleted region of the X-ray CCD. Events from the undepleted bulk can be used for retrieving information regarding the energy of the corresponding X-ray photon [3]. In Astronomy CCDs, a certain signal loss mechanism limits realization of the state-of-the-art device for X-ray detection over the energy of 0.1-10 *keV*. Quantum efficiency loss at X-rays below 1 *keV* occurs through absorption into the passivated dielectric layers and the electrode structure as dead layers. For X-rays above 4.5*keV*, most of the X-ray interactions are in the depletion layer, field-free region or p^+-substrate region due to the large absorption depth. In the latter cases the charge diffusion will result in poor spatial resolution due to the lateral diffusion. Thus, for a good charge detection of X-rays below 1*keV* and above 4.5*keV* and for long wavelength IR (>750*nm*), a CCD pixel should have an optimized structure with a thinner dead layer for efficient low energy X-ray detection and a thicker photo-sensitive layer for high energy X-ray detection.

For the latter requirement, a high-purity bulk or substrate material is employed [1, 2, 4]. The "JET-X CCD"[1, 2, 4] is one such device under development by the X-ray astronomy group of the Leicester University in collaboration with EEV Ltd. for the JET-X instrument on the Soviet mission Spectrum-X.

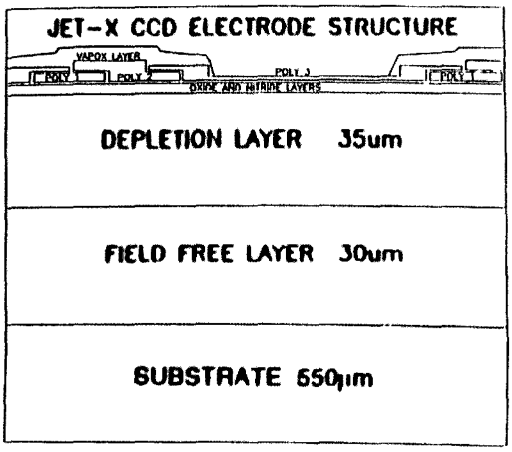

Fig. 1. Cross section of a JET-X CCD structure.

The "EVEREST" simulation package, a semiconductor device simulator, was chosen to investigate its electrical properties [5]. This uses a finite-element method with an adaptive mesh technique for higher accuracy, lower computation time and efficient memory usage. Local efficient mesh refinement allows rapid variation of the charge current near the interfaces between the diffusion contact and input / output gate, and between the input gate and the first gate electrode, as well as in the fast changing distribution of channel doping etc. Finite-element simulation is achieved using discretized semiconductor

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equations, resulting in the transformation of non-linear equations into linear ones. This permits the geometry and mesh size to be more flexible than the finite difference technique.

A 3-D CCD simulation was performed to obtain an accurate potential profile, including mobile signal charge, in which Poisson's equation and the current-continuity equation are simultaneously solved. Some results for the potential minimum and barrier height for efficient charge storage and transfer are demonstrated. Different depletion edges obtained from the simulation are compared with those estimated from the detection efficiency measurements. We also present a result of signal charge movement obtained from a time-dependent simulation. In previous work [6-8], more detailed simulation results obtained from BC MOSFET [6, 7] and CCD [6, 8] have been shown to be in good agreement with the measurements.

2. Description of the Device

A front-illuminated CCD was developed for the Joint European X-ray Telescope (JET-X) to optimize the X-ray detection properties of the energy range of 0.3 to 10 *keV* (42Å to 1.2Å) [3]. The device consists of an array of 768×1024 $27\mu m$ square pixels, fabricated on a high resistivity ($1.5k\Omega$-cm) 65 thick epi-layer on a $550\mu m$ thick p^+ substrate. This device has a large area of 20.7 x 27.6 mm^2 which is divided into two identical sections for imaging and storage. Thus, it can be operated in frame transfer or full area imaging. It has a wide column buried channel (BC) implant to increase depletion depth, but with an additional narrow BC implant to confine charge during transfer and to increase radiation hardness [2]. In Fig. 1, a device schematic is illustrated, where a phase 3 electrode structure was modified to improve the spectral response at X-rays below 1 *keV* by thinning one electrode, and the depletion depth and field-free layer are ~ 35 μm and ~ 30 μm, respectively. The pixel is covered with 3 poly electrodes. 2 of 5 μm and one thin extended poly-silicon electrode of 17 μm to improve a low energy transmission. The device includes both wide and narrow channels in which the former is used for deep depletion, while the latter is used for radiation hardness.

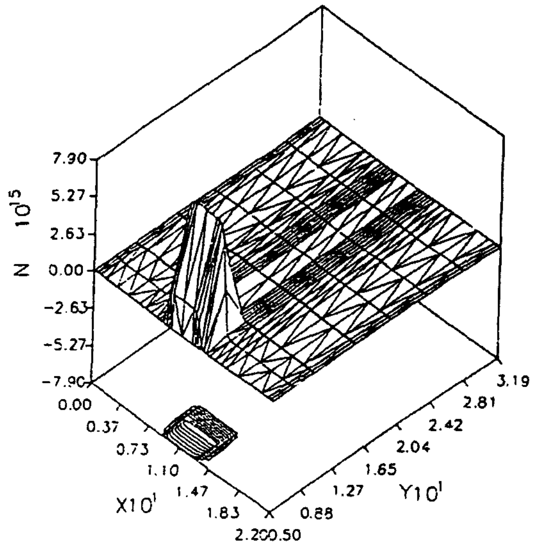


Fig. 2. The isometric electron distribution on a potential minimum. The x-direction displays the channel width and y-direction represents the channel length.

3. Results and Discussion

An electron charge distribution extracted on a potential minimum in the channel is presented in Fig. 2, where the first (or second) phase electrode with a gate length of 5 μm was applied to 10 V, while the second (or first) and third remained unchanged at 0 V. To transfer the whole signal from one storage region to the next without surface charge trapping, the potential difference between the surface interface and channel minimum point should be > 10 kT/q in order for the mobile charge not to jump the barrier for the duration of the transfer process.

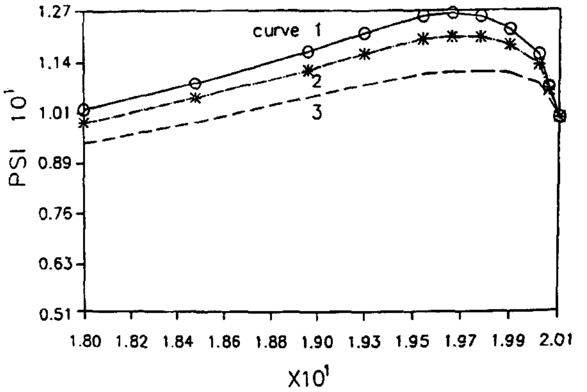


Fig. 3. Potential minimum variation, as a function of mobile charge, along the direction normal to the surface: curves 1, 2 and 3 are described in the text.

In Fig. 3. the potential distributions are shown in the direction normal to the surface as a function of mobile carrier densities, which are extracted at the center of gate 1. In this static simulation an input circuit consisting of an input diffusion contact and input gate was used to control a charge injection. The flat band voltage was assumed to be zero. In curve 1 the potential well is filled with < 50 electrons, resulting in a potential difference of 1.1 V (although it is typically 1 V) between the potential minimum and the surface potential. The potential minimum was reduced by 0.9 V compared with that under no mobile charge, which corresponds to 13.5 V. For curve 2 the potential well is filled with 19136 electrons and then the resulting barrier height is reduced to 0.6 V. In this case the potential minimum is located at 0.38 *μm* below the surface.

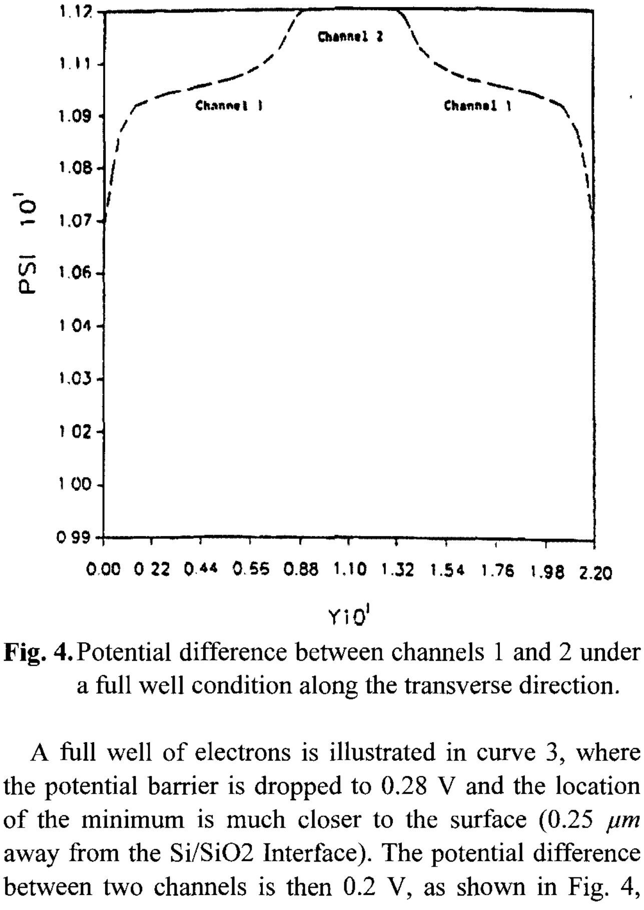


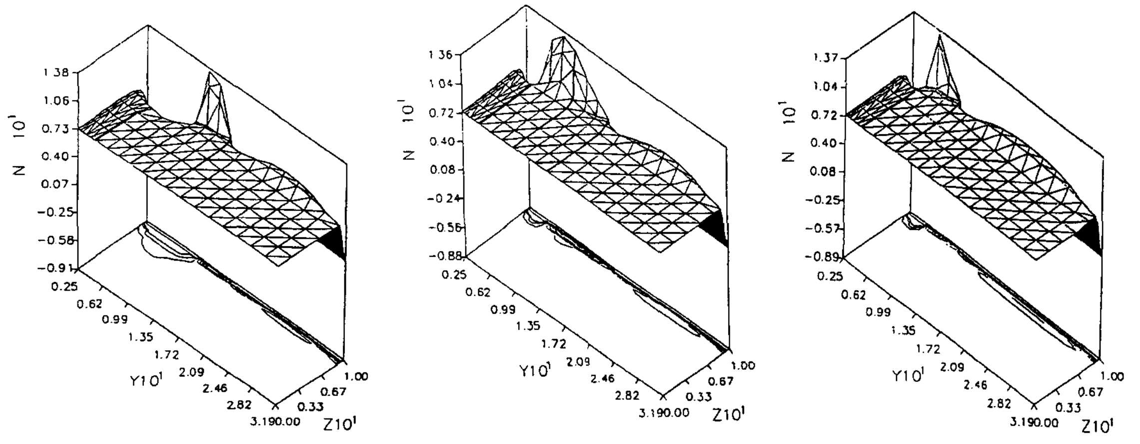
Fig. 4. Potential difference between channels 1 and 2 under a full well condition along the transverse direction.

A full well of electrons is illustrated in curve 3, where the potential barrier is dropped to 0.28 V and the location of the minimum is much closer to the surface (0.25 *μm* away from the Si/SiO2 Interface). The potential difference between two channels is then 0.2 V, as shown in Fig. 4, which can ensure good charge confinement in channel 2. The channel isolation regions located at both ends of the channel width are not shown in Fig. 4. The static charge carrying capacity for this full well condition in the supplementary channel 2 then corresponded to 56160 electrons.

In order to estimate the depletion depth of a JET-X CCD, different operating voltage conditions as a function of the substrate bias have been used in the simulation. We have analyzed different depletion edges to give some comparisons with the estimated edges from the detection efficiency measurements. They have been estimated based on the number of the pixels for each event due to the splitting of charge during the charge collection process. For this work McCarthy [4] found the corresponding quantum efficiencies, from which different depletion depths have been estimated. For the present work three different depletion edges were classified: strong-field, light-field and zero-field depletion edges. Their definition and extraction method have been presented in Reference [6].

In Table I. the results obtained from the simulation as a function of substrate bias were summarized and compared with those from the measurement, where x_s, x_l and x_0 are represented as strong, light and zero-field edges, respectively. In this simulation only a wide (phase 3) gate was applied to 10 and 12 V. For the depletion edge with the strong field the simulated results demonstrated that their increment as a function of the gate and substrate bias voltage was approximately linear, resulting in an average error of approximately 5% compared with the results estimated from X-ray measurements. Also, the zero-field depths simulated provided very good prediction for analysis of the photo-sensitive volume. They involved only approximately 2.3% as an average error [6]. Also, a comparison of the total depletion depth x_l obtained from 3-D and 1-D analysis as a function of the substrate bias showed that the overestimated channel potential computed in 1-D analysis gave rise to a little higher depletion depth.

A result of the transient simulation for signal charge movement within the potential well in channel 2 is illustrated in Fig. 5, where Poisson's equation and current-



(a) (b) (c)

Fig. 5. The electron charge transfer: (a) charge stored under gate 1 at t=400 ns; (b) charge transfer from gate 1 to gate 2 at t=500ns; (c) a complete charge transfer under gate 2 at t=650 ns. The magnitude is shown as LOG scale.

continuity equations have been solved with electron and hole carriers resulting in a very high accuracy but long computation time. A three-phase JET-X CCD with low charge Packet was simulated as a function of time, in which a clock Period of 0.5 μs with rise and fall times being 0.1 μs and 0.15 μs, respectively was employed with a clock voltage swing of 8 V. A charge transfer process between phase 1 and phase 2 is indicated in Fig. 5. The mobile charge is filled under gate 1 at 0.4 μs, as shown in Fig.. 5a, and discharge is started at 0.5 μs as illustrated in Fig. 5b. Whilst in Fig. 5c, the charge transfer is completed under gate 2 at 0.65 μs. From this transfer process it was seen that the charge packet size transferred under gate 2 was slightly increased compared to that under gate 1. This is probably because some of the fixed charge impurity into the potential well underneath phase 2 remained unneutralized and was added into the net charge packet. For charge transfer with a large charge packet the effect of the fixed impurity on the leakage condition can be neglected.

Table 1. Comparisons between different depletion edges simulated and edges estimated

	Depletion Depth(μm)									
	V_{g3}=10V, V_{g1}=V_{g2}=0V					V_{g3}=12V, V_{g1}=V_{g2}=0V				
V_{ss}	Simulated			Estimated		Simulated			Estimated	
	x_s	x_l	x_0	x_s	x_0	x_s	x_l	x_0	x_s	x_0
0	34.9		65.7			35.7		65.6		
1	34.3	42.9	65.8	30.9	64.6	34.9	43.2	65.6	33.8	66.3
2	33.4	42.1	65.1	30.6	62.8	34.3	42.8	66.0	32.3	64.4
3	31.3	41.1	65.0	30.7	63.4	33.5	42.1	68.2	31.4	65.0
4	27.8	35.8	65.0		63.8	31.5	41.1	65.0	30.5	64.0
5	26.5	35.7	65.0	29/2	65.5	28.0	36.7	65.0	30.0	63.4

4. Conclusion

Buried channel CCDs with deep depletion have been analyzed to provide an optimized condition for charge storage and transfer, as well as to estimate different depletion edges for the charge detection efficiency in the device. A maximum charge capacity has been found for the narrow channel by considering the potential distribution as a function of mobile charge. Analysis for the depletion depths of JET-X CCDs have been successfully performed, showing good agreement with the depths estimated from X-ray detection efficiency measurements. It is evident that the "EVEREST" simulation package is a very useful tool, which led us to study the optimization work of BC CCDs.

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