THE EFFECTS OF BULK TRAPS ON THE PERFORMANCE OF BULK CHANNEL CHARGE-COUPLED DEVICES

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ABSTRACT

The effects of trapping of the signal charge in bulk traps, which exist at discrete energy levels in the buried channel, on the transfer efficiency and transfer noise in bulk channel charge-coupled devices (BCCDs) are presented. The effects of the charge packet size and frequency on the transfer efficiency and transfer noise in BCCDs are calculated and compared with experimental results, and the distribution and density of bulk states are measured. A transfer inefficiency of 3×10^{-5} per transfer is measured. Two bulk traps with densities of 1.2×10^{11} cm^{-3} and 1.8×10^{11} cm^{-3} and emission time constants of 275 μsec and 0.3 μsec, respectively, are identified.

I. INTRODUCTION

Bulk Channel Charge-Coupled Devices (BCCD) were first introduced (ref. 1) in order to avoid the transfer inefficiency and noise limitations expected in surface channel CCDs (SCCD) due to the interaction of the signal charge with interface states (ref. 2-4). Bulk channel CCDs are also subject to similar but normally smaller effects, which can be attributed to the interaction of the signal charge with bulk states, and are the subject of this paper.

II. INCOMPLETE CHARGE TRANSFER WITHOUT BACKGROUND CHARGE

We shall assume an n-channel BCCD with a uniform density N_t of bulk traps at energy level E below the conduction band. The density of filled states is described by the Shockley-Read-Hall (ref. 5) rate equation

$$\frac{dn_t}{dt} = \frac{(N_t - n_t)}{\tau_t} - \frac{n_t}{\tau_e} , \qquad (1)$$

where τ_t and τ_e are the trapping and emission time constants of the trap center and are given by

$$\tau_t = \frac{1}{\sigma v_{th} n_o} ; \qquad \tau_e = \frac{1}{\sigma v_{th} N_c} \exp\left(\frac{E}{kT}\right) \qquad (2)$$

where n_o is the volume density of mobile electrons, σ is the trap capture cross section for electrons, v_{th} is the average thermal velocity of the mobile electrons, N_c is the effective density of states per unit volume in the conduction band.

Since for most traps of importance the trapping time constant is much less than the re-emission time constant, the charge trapped in bulk traps from a signal charge stored under an

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electrode and occupying a volume V_s in the bulk at moderate and low clock frequencies is given by

$$q_t = \int_{V_s} \frac{eN_t d_V}{1 + \frac{N_c}{n} \exp(-E/kt)} \approx eN_t V_s \qquad (3)$$

At high frequencies the traps may not all be filled. For example, with $n_o = 10^{15}$ cm^{-3}, $\sigma = 10^{-15}$ cm^2 and $v_{th} = 10^7$ cm sec^{-1}, $\tau_t = 0.1$ μsec. Therefore bulk trapping effects will decrease for frequencies ≥ 10 MHz. We consider first a multiphase CCD where all electrodes are equivalent, such as a three-phase CCD. We can assume an instantaneous transfer of the free charge from under one electrode to the next at the appropriate time. In the next period of time $T = 1/mf_c$, where m is the number of phases and f_c is the clock frequency, the emitted carriers move forward to join the main signal packet. However, the amount of trapped charge which cannot join the signal charge packet is then given by

$$\Delta q = eN_t V_s e^{-\left(\frac{T}{\tau_e}\right)} \qquad (4)$$

If a given charge packet is followed by a string n_z of empty charge packets, the filled bulk states continue to emit trapped charge, into the empty charge packets. When the next signal charge packet comes along, the bulk states are filled again by capturing charge ΔQ_s per transfer from this packet. This charge appears as a charge loss $n\Delta Q_s$ from the leading charge packet of a string of charge packets transferred through a device with n electrodes when preceded by n_z empty charge packets. ΔQ_s is given by Eq. (5) as the difference between the total number of filled traps given by Eq. (4) and the number of traps that remain full after time $(n_z mT)$ so that

$$\Delta Q_s \cong eN_t V_s e^{-T/\tau_e}\left[1 - e^{n_z mT/\tau_e}\right]. \qquad (5)$$

In a similar manner we can calculate the charges $\Delta Q_{(1)}$, emitted into the first trailing empty charge packets after a string of signal charge packets.

$$\Delta Q_{(1)} = eN_t V_s e^{-T/\tau_e}\left[1 - e^{-mT/\tau_e}\right] \qquad (6)$$

In the case where several bulk states with different densities and emission time constants interact with the signal charge, the right hand sides of Eqs. (5) and (6) will be the sum of similar terms corresponding to each of the bulk states.

In other types of devices, such as a two-phase BCCD (ref. 6) half the electrodes act as transfer gates and the effect of the partial filling of the bulk states under these gates as the charge moves by should be considered.

It is clear that these charge deficits or excesses are dependent on the ratio of T/τ_e, which involves the clock frequency and the energy level of the bulk state. This is in contrast to SCCDs where there is a continuum of interface states across the bandgap. Also the exponential saturation of the charge deficit with the increasing number of empty charge packets n_z in BCCDs differs from the continuously (logarithmically) increasing value of charge deficit in SCCD.

III. INCOMPLETE CHARGE TRANSFER WITH CIRCULATING BACKGROUND CHARGE

A background charge may be inserted at the input end of the device so as to reduce the incomplete charge transfer effects. The distribution of charge normal to the surface in the buried channel can be obtained for different charge packet sizes by numerically solving the one-dimensional Poisson equation (ref 7). This was done for a doping profile in the buried channel that was assumed to be Gaussian with a peak surface concentration of $1.6\times10^{15}/cm^3$ and channel depth of 2.1 microns. The distance over which the charge packet spreads versus the charge packet size for gate voltages of 0 and 10 volts is shown plotted in Fig. 1. As the size of the charge packet increases, its volume in the buried channel first rapidly increases as it fills the bottom of the potential well, then increases almost linearly. Thus a little background charge or slim zero is expected to improve the performance until the linear part of the curve is reached, i.e., the BCCD is essentially limited by a volume "edge effect" (ref. 2). In treating the trapping and release of charges by the bulk states in the buried channel with a background charge one must consider the ways in which the different volumes of the buried channel surrounding the volume filled by the background charge interact with the charge packets.

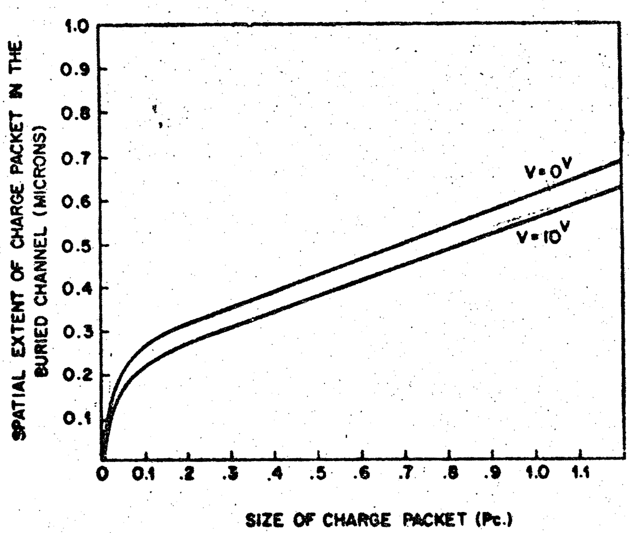


Fig. 1 The spatial extent of the charge in the buried channel for different charge packet sizes at gate voltages of zero and ten volts. The doping profile is Gaussian with a surface concentration of $1.6\times10^{16}/cm^3$ and a 2.1 μm deep channel.

IV. INTRODUCTION OF TRANSFER NOISE BY BULK STATES

Similar to the effects of interface states in surface channel CCDs (ref. 2) the constant filling and emptying of the bulk states, as a signal charge moves along the buried channel in a BCCD, can introduce fluctuations in the number of carriers in the signalcharge packet. This we call transfer noise. An expression for the fluctuations introduced by trapping in a bulk state may be derived in the following way.

The trap center is considered to be full and starts to emit the trapped carriers at $t = 0$ when the mobile carrier density $n_o \sim 0$. It is assumed that the trapped carriers, which are emitted, are transferred each cycle. The probability P of a carrier trapped in a bulk state of emission time constant τ_e being emitted in time t is given by

$$P \equiv 1 - \exp\left(-\frac{t}{\tau_e}\right) \tag{6}$$

The distribution of full and empty bulk states will be binomial with a variance V_n per unit volume of the buried channel given by

$$V_n = N_t e^{-t/\tau_e}(1-e^{-t/\tau_e}). \tag{7}$$

Unlike SCCDs the variance in the number of trapped carriers emitted will depend on the signal charge in the preceding charge packets. Since an excess of carriers re-emitted into one charge packet leads to an equal deficit in the succeeding packet, at each transfer the two fluctuations must be summed. In the case where all the charge packets are equally full the mean square fluctuation is double the variance and is given by

$$F^2 = 2V_s N_t e^{-T_c/m\tau_e}\left[1-e^{-T_c/m\tau_e}\right]. \tag{8}$$

It follows that the maximum mean square fluctuation F^2 is given by

$$F^2 = 0.5\ V_s N_t, \tag{9}$$

This maximum noise will occur at a transfer frequency given by

$$f_o = \frac{1.45}{m}\frac{1}{\tau_e}. \tag{10}$$

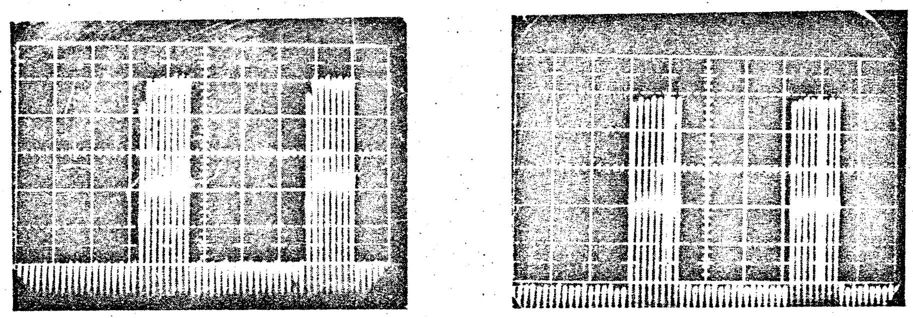
Since the noise due to trapping in the bulk states between neighboring charge packets is correlated, the current noise spectrum S(f) in the output signal will depend on the frequency f just as for interface states (ref. 8)

$$S(f) = 2f_c F_T^2 \left(1 - \cos\frac{2\pi f}{f_c}\right) \tag{11}$$

Since several bulk traps may be active, the fluctuation contribution from each of them will have to be summed.

V. EXPERIMENTAL RESULTS

We have measured the transfer properties of a 256-bit three-phase three-level metallization BCCD (ref. 9). The length of the polysilicon electrodes is 10 μm and the channel width is 200 μm. The buried channel was obtained by implanting 1.5×10^{12} phosphorus ions in a p-substrate of doping $4.5\times10^{14}/cm^3$. After several anneal and oxide growth cycles, the doping profile in the buried channel was found (ref 10) to be almost Gaussian with a surface concentration of $1.6\times10^{16}/cm^3$ and channel depth of 2.1 microns.



WITHOUT BACKGROUND CHARGE   WITH 10% BACKGROUND CHARGE

Fig. 2 Appearance of two groups of six and five "ones" separated by 18 and 4067 "zeros" at the output of a three-phase 256-bit BCCD operated at 6 MHz.

Figure 2 shows the output from a BCCD operated at a clock frequency of six megahertz with two groups of six and five "ones" separated by 18 and 4067 "zeros" respectively. The leading charge packet of each group shows a charge deficit as it has to replenish all the charge emitted from the bulk states in the buried channel since the last passage of a "one" charge through the device.

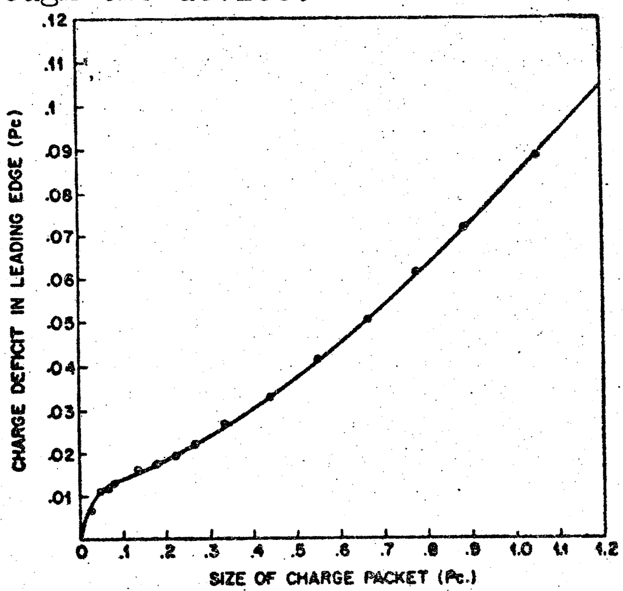


Fig. 3 Charge deficit at the leading edge of a group of six "ones" separated by 4090 "zeros" versus the size of the charge packet for a three-phase BCCD operated at 1 MHz.

Figure 3 illustrates the charge deficit in the leading charge packet of a group of "ones" following 4090 empty charge packets. The shape of this curve, particularly the sharpe rise at small charge packets corresponds to the shape of the spatial extent of the charge packet in the buried channel plotted in Fig. 1. The data in Fig. 3 fitted to Eq. (4) indicate an average effective density of states of $2\times10^{11}/cm^3$ in the bulk. The nonlinearity at large packet sizes can be explained by an increase of bulk states towards the silicon-oxide interface, perhaps explained as unannealed ion implant damage. The effect of a background charge on the charge deficit of the leading station and the charge excess in the trailing station of a group of eight "ones" separated by 4088 "zeros" is quantitatively shown in Fig. 5 of the next paper. Even with no intentionally introduced background charge, the charge deficit from the leading charge packet is only 8.9%. By adding a background charge,

Theory is for one trap level

the charge deficit at the leading edge and the charge excess at the trailing edge decrease rapidly and reach a constant value of 2.2% and 1.7% respectively after about 10% background charge. This is equivalent to a transfer inefficiency of about 3×10^{-5} per transfer, which is close to the limit of measurement for a single passage through a 256-bit device.

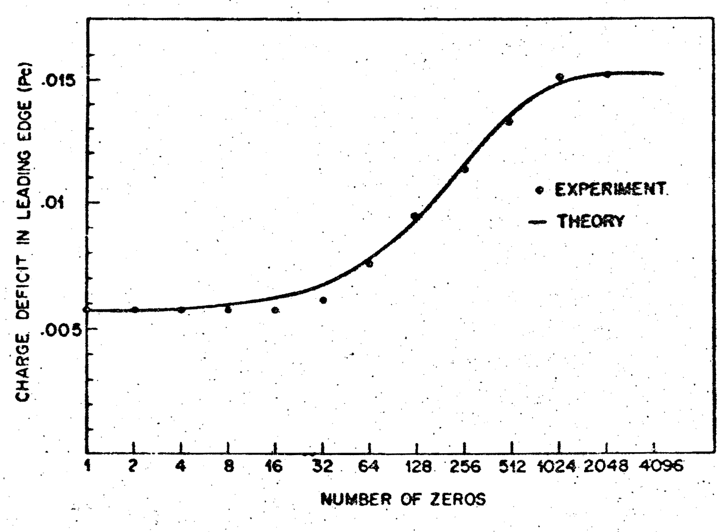


Fig. 4 Charge deficit in the first "one" for a BCCD operated at 1 MHz as a function of the number of "zeros" between the group of "ones". The solid curve is calculated from Eq. (5).

In Fig. 4 the charge deficit from the leading "one" is plotted versus the number of "zeros" between the groups of "ones". As expected according to the model described above based on two localized bulk states interacting with the signal charge, the charge deficit shows the exponential saturation behavior expected from Eq. (6). The data presented in Fig. 5 when fitted to Eq. (4) in addition to other data taken at 6 Megahertz clock frequency indicate that bulk states of emission time constants of 275 µsec and 0.3 µs with densities of $1,2\times10^{11}/cm^3$ and $1.8\times10^{11}/cm^3$ respectively interact with the signal charge.

Noise measurements have been carried out on the three-phase BCCDs, (ref. 5) but the limit of measurement sensitivity was 250 rms electrons per charge packet. Our measurements indicated that the BCCD measured had a transfer noise component less than this limit.

Using the bulk trap densities and distribution obtained from the charge deficit calculations in Fig. 5 the mean square fluctuation in a charge packet is calculated from Eq. (8) for a charge packet of 0.17 pC after transfer along the 256-bit three-phase BCCD and plotted in Fig. 5 versus clock frequency. Using the data in Figs. 1 and 6 we have also plotted the transfer noise versus the size of the charge packet in Fig. 6. Noise measured in a SCCD with the same geometry is also plotted.

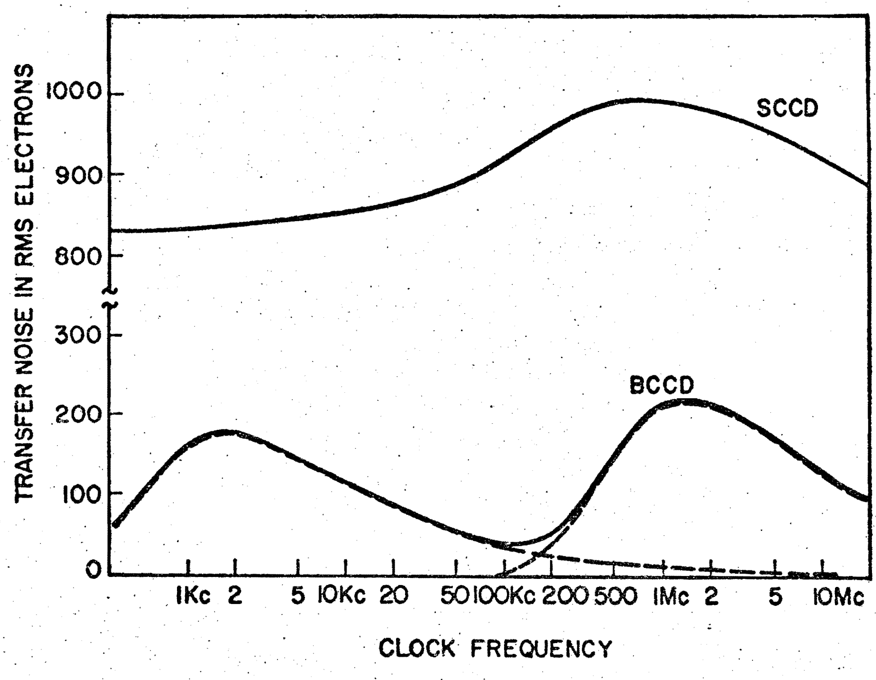


Fig. 5 Transfer noise in BCCD and in SCCD versions of a three-phase 256-bit device, versus clock frequency. 200μm channel

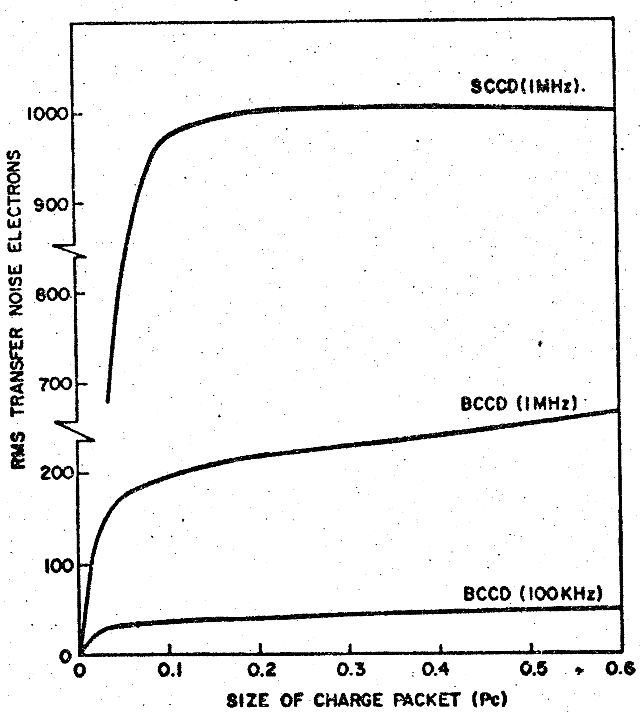


Fig. 6 Transfer noise in BCCD and in SCCD versions of a three-phase 256 bits device, versus charge packet size.

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