

THE PERISTALTIC CHARGE COUPLED DEVICE

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Abstract

In charge transfer devices the transfer speed is mainly determined by the transport of the last fraction of each charge bunch.

In a PCCD the transport of especially the last fraction takes place at a substantial distance from the electrodes in the bulk of a semiconductor, where the drift fields are appreciably higher than at the oxide semiconductor interface.

A four phase PCCD with $7.5\mu\text{m}$ gates on top of a homogeneous N-type layer on a high ohmic P-type substrate shows high transfer efficiencies ($>99,99\%$) up to rates of over 100 MHz. Operation of this device up to 1 GHz is expected to be feasible.

The PCCD with the homogeneously doped layer has for bulk operation in comparison with a surface CCD, with the same oxide thickness - a smaller signal charge handling capacity. This is caused by the larger effective distance between the charge and the electrodes.

The charge handling capacity of the PCCD is strongly improved by using a low doped N-layer with a thin strongly doped N-type top layer. Now the main part of the charge is at a small distance to its electrode, still the last fraction is transferred at a substantial distance.

It will be shown that this type of PCCD combines the advantages of a surface CCD and a bulk CCD.

1. Introduction

The PCCD belongs to the class of C(harge) T(ransfer) D(evices). CTD's are B(ucket) B(rigade) D(elay) lines and C(harge) C(oupled) D(evices). The last mentioned devices can be divided into two different species dependent on the type of operation. The first one is the S(urface) CCD, in which the transfer of charge is along the Si-SiO₂ interface. The second one is the B(ulk) CCD in which the transport of charge is in the bulk of the semiconductor. The PCCD belongs to the class of BCCD's. Other types of BCCD's are given in [1] and [2].

In a PCCD mobile carriers in the bulk of a semiconductor are used and the transfer of the last carriers takes place at a substantial distance from the transferring electrodes. These last fractions are constrained between the depletion regions produced by charge transfer electrodes and by an underlying substrate. The manner of charge transfer in the PCCD has some resemblance with the way an "oesophagus" functions. From this the description "peristaltic" has been taken.

Depending on the ratio $\frac{L}{d_2}$ (fig. 1) we distinguish:
(a) self-induced-field type (SF-type) ($L \gg d_2$). For this type the charge transfer is determined by drift fields, caused by variations in carrier density, and by diffusion.
(b) externally-induced-field type (EF-type). For this type L is of the same order of magnitude as d_2 . Drift fields directly induced by external voltages on the electrodes (fringing fields) become dominant for the charge transfer.

Depending on the dope profile perpendicular to the electrodes we distinguish a PCCD with a homogeneously doped layer and a PCCD with a dope profiled layer.

1.1 Homogeneously doped PCCD

Here one has an N-type epitaxial homogeneously doped layer on a P-type substrate. Depending on the dope levels and the substrate voltage, charges can be transported in the surface mode, the bulk mode, or

in a combination of these two.

(a) The surface mode

This is achieved when the substrate-N-layer depletion region reaches the Si-SiO₂ interface. Then the device operates in the same manner as the conventional surface CCD [3].

(b) The bulk mode

This type of operation has been treated in [4]. Now all the charge is kept in the bulk (no accumulation at the Si-SiO₂ interface), where much higher drift fields exist than at the surface, leading to much shorter transfer times. Because the transport of charge is not at the Si-SiO₂ interface the surface states have no effect on the charge transfer efficiency. Only trapping centers in the bulk will influence the charge transfer efficiency. With the present state of technology the number of these centers can be much lower than that of the surface states. However the charge handling capacity of the bulk mode operation is lower than that of the surface mode. This is due to the larger effective distance of the charge to its electrode.

(c) The combined surface and bulk mode

In this mode the charge transfer occurs partly along the surface while the last fraction is transported in the bulk. In this mode of operation the advantages of the two modes mentioned above are combined. These are the large charge handling capacity of the surface mode and the high speed of the bulk mode. However it must be borne in mind that the surface states determine the transfer efficiency with the present state of technology.

1.2 Dope profiled layer PCCD

In the PCCD, with a profiled layer, these surface states effects can be avoided, while at the same time the charge handling capacity can be comparative to the surface mode.

Here one has a very thin relatively high doped N-type layer on

top of a relatively thick and low doped N-type layer. Most of the charge is present in the highly doped top layer and thus very near to its electrode resulting in a low clock voltage (large charge handling capacity).

2. Principle of the charge transfer

2.1 Self-induced-field type ($L \gg 2$)

In this case fringing fields can be neglected. Using a one dimensional model, the charge transfer equation (eq. (2.3)) may be derived with of the aid of the relationship

$$J = \varphi \mu E - D \frac{\partial \varphi}{\partial x} \quad (2.1)$$

and the divergence equation for current

$$\frac{\partial \varphi}{\partial t} = - \frac{\partial J}{\partial x} \quad (2.2)$$

$$\frac{\partial \varphi}{\partial t} = \frac{\partial (D_{\text{eff}} \frac{\partial \varphi}{\partial x})}{\partial x} \quad (2.3)$$

2.1.1. Homogeneously doped PCCD

(a) surface mode operation

For the surface mode operation the transfer behaviour is identical to that of the surface CCD [5], [6]. The p-type substrate is set at a high negative voltage inducing a field by which the charge is driven to the Si-surface. Fig. 2 shows the situation for a single transfer at some time after initiation of the charge transfer. At $X=L$ (channel pinch off point) the charge concentration is supposed to be zero. At $X=0$ the gradient of the charge is supposed to be zero. The drift-field in the transport direction can be approximated by

$$E = - \frac{d_1}{\epsilon_1} \frac{\partial \varphi}{\partial x} \quad (2.4)$$

The capacitance of the charge to the substrate has been neglected. In equation (2.3)

$$D_{\text{eff}} = \mu \left(\varphi \frac{d_1}{\epsilon_1} + \frac{kT}{q} \right) \quad (2.5)$$

For the remaining charge at time t we define

$$\varphi_r = \frac{1}{L} \int_0^L \varphi(x, t) dx \quad (2.6)$$

and for the initial charge

$$\varphi_i = \varphi_r(0) \quad (2.7)$$

Numerical solution of the charge transfer (eq. (2.3)) with $Q_i = 5 \times 10^{11}$ C/cm² is shown in fig. 5 (curve 1), where

$$\epsilon = \frac{\varphi_r}{\varphi_i} \quad (2.8)$$

It can be seen that after a few times T the fractional remaining charge (ϵ) is less than a few percent, and the main part of the transfertime is determined by the last fraction. So one gets a considerably improved transfer when the transfer for the last fraction of the charge is accelerated.

(b) bulk mode operation (fig. 3)

For simplicity we suppose a very high ohmic substrate, so we can neglect the depletion region in the N-layer, caused by the negative biased P-substrate, as well as the charge-substrate capacitance. By using the gradual channel approximation of Shockley we derive for the self-induced drift field

$$E = - \left(\frac{d_1}{\epsilon_1} + \frac{d}{\epsilon_2} \right) \frac{\partial \varphi}{\partial x} \quad (2.9)$$

and for the effective diffusion coefficient of eq. (2.3)

$$D_{\text{eff}} = \mu \left[\varphi \left(\frac{d_1}{\epsilon_1} + \frac{d}{\epsilon_2} \right) + \frac{kT}{q} \right] \quad (2.10)$$

In eq. (2.9) and (2.10) the term d is place and time dependent. When initially the bulk is completely filled then d varies from zero to approximately d_2 during transfer. One may expect an effective value (d_{eff}) which lies between zero and d_2 . Calculations show that d_{eff} is almost equal to d_2 . (fig. 5, curve 2, $N_d = 10^{15}$ cm⁻³). This is due to the fact that the last fraction of the charge, which determines the transfertime, is almost at a distance of d_2 . This means that in

principle the transfer behaviour in the bulk mode is almost the same as in the PCCD surface mode of operation with an increased oxide thickness of

$$t_{ox} = B d_1 \quad (2.11)$$

where

$$B = \left(1 + \frac{d_2 \epsilon_1}{\epsilon_2 d_1}\right) \quad (2.12)$$

This decreases the self-induced transfer time constant by a factor of B [4].

The minimum clockvoltage for a B times thicker oxide will increase with a factor of B for the same amount of charge. However for the bulk mode operated PCCD this factor will be

$$C = \left(1 + \frac{d_2 \epsilon_1}{2 \epsilon_2 d_1}\right) \approx \frac{B}{2} \quad (2.13)$$

because the effective distance of the completely filled bulk charge is

$$C d_1 \approx \frac{B}{2} d_1 \quad (2.14)$$

The degree of doping of the P-substrate and the N-layer does not significantly alter the principle of operation of the device (fig.6). It can be shown that B is the ratio of the oxide capacitance to the parallel capacitance of the charge bunch at pinch off (d_{21}) to its electrode and substrate.

$$B = \frac{d_{22} \left(1 + \frac{N_d}{N_a}\right) \left(1 + \frac{d_{21} \epsilon_1}{\epsilon_2 d_1}\right)}{d_1 + d_{22} \frac{N_d}{N_a} + \frac{\epsilon_2 d_1}{\epsilon_1}} \quad (2.15)$$

(c) surface and bulkmode operation

In the following considerations, for convenience, we will suppose a very high ohmic substrate.

Fig. 4 shows the situation as a charge packet is transferred. At $X=X_1$ the accumulation charge is zero. During transfer X_1 moves from $X=L$ to $X=0$. For the self-induced

drift fields one finds

$$E = -\frac{d_1}{\epsilon_1} \frac{\partial \psi}{\partial x}, \quad 0 < X < X_1 \quad (2.16)$$

and

$$E = -\left[\frac{d_1}{\epsilon_1} + \frac{d}{\epsilon_2}\right] \frac{\partial \psi}{\partial x}, \quad X_1 < X < L \quad (2.17)$$

These yield to the corresponding effective diffusion coefficients given by eq's (2.5) and (2.10). The bulk- and surface-mobility are assumed to be alike, so that Q and $\frac{\partial \psi}{\partial x}$ are continuous at the moving boundary X_1 .

A result of the numerical solution of the charge transfer equations is shown in fig. 5 (graph 3) for $N_d = 2 \times 10^{14} \text{ cm}^{-3}$. When the surface charge dominates the transfer process, curve 3, follows approximately curve 1 of the surface mode. After a few time constants, when the accumulation charge has disappeared, ($X_1 \approx 0$) curve 3 follows almost curve 2 (bulk transfer). Curve 3 is almost identical to curve 2, when curve 2 is shifted to the right by an amount almost equal to the time needed for the transfer of the surface accumulation charge (in this case 80%). Numerical calculations show that this still holds when the difference in surface- and bulk-mobility is taken into account.

The time needed for the transfer of the first 80-95% of the charge is negligible compared to the transfertime of the last fraction. Thus the device behaves almost as if all the charge is at the pinch off level (d_2). When we use e.g. trapezoidal clockpulses, the minimum necessary top to top clockvoltage \hat{V} is then given by

$$\hat{V} = \psi \frac{d_1}{\epsilon_1} + N_d \frac{d_2^2}{2 \epsilon_2} = \quad (2.18)$$

$$= V_s + V_e$$

For the surface mode of operation, which has the highest charge handling capacity, the minimum clock-

voltage is V_s (eq. (2.18)). The extra necessary clock voltage V_e , caused by the bulk charge, is shown in fig. 7. V_e can considerably be reduced by decreasing the dope level of the N-layer. We see, with an extra voltage of some volts (N_d small), this type of PCCD has the same charge handling capacity as for the surface mode of operation. From the point of view of the charge transfer it behaves as a CCD with a substantially thick oxide (eq. (2.11)). It is obvious that with the present state of technology the transfer efficiency is determined by the surface states for this mode of operation. The following device, however, combines the advantages of the surface and bulkmode operation, while avoiding the influence of the surface states.

2.1.2. Dope profiled layer PCCD

As has been shown, when the last fraction of the charge is transferred at a depth of d_2 , from the point of view of the charge transfer the device behaves as if all the charge is transferred at that depth. Consequently, in principle the transfer inefficiency (ϵ) is almost decreased by the corresponding factor B (eq. (2.12) and fig. 5) in comparison with the surface mode of operation. By storing the former accumulation part, very near its electrode, in a very thin relatively high doped N_1 -layer on top of a substantially thick and relatively low doped N_2 -layer, (fig. 8) then all the charge is confined to the bulk and the influence of the surface states is eliminated.

For both regions $0 < x < X_1$ and $X_1 < x < L$ equations (2.9) and (2.10) are valid. At the moving boundary X_1 , Q and $\frac{\partial \psi}{\partial x}$ are continuous. The graph, from numerical calculations of the appropriate transfer equations, as one should expect, is found to lie between graph 3 and 2 of fig. 5. Where

$$\begin{aligned} N_1 &= 1.4 \times 10^{16} \text{ cm}^{-3} & d_3 &= 0.3 \text{ } \mu\text{m} \\ N_2 &= 2 \times 10^{14} \text{ cm}^{-3} & d_2 &= 5 \text{ } \mu\text{m} \\ Q_1 &= q \times 5 \times 10^{11} \text{ cm}^{-2} & d_1 &= 0.1 \text{ } \mu\text{m} \end{aligned}$$

was taken.

If the bulk is completely filled the depth (Z) of the center of gravity, from the Si-SiO₂ interface, of the charge profile is given by

$$Z = \frac{(N_1 - N_2) \frac{d_3^2}{2} + N_2 \frac{d_2^2}{2}}{(N_1 - N_2) d_3 + N_2 d_2} \quad (2.19)$$

The effective distance of the charge to its electrode is

$$d_z = d_1 + \frac{\epsilon_1}{\epsilon_2} Z \quad (2.20)$$

The minimum necessary clock voltage \hat{V} is found to be

$$\hat{V} = V_s + V_e = \varphi \left(\frac{d_1}{\epsilon_1} + \frac{Z}{\epsilon_2} \right) \quad (2.21)$$

When we suppose:

$$\begin{aligned} Q_1 &= q \cdot 10^{12} \text{ cm}^{-2} & d_1 &= 0.1 \text{ } \mu\text{m} \\ N_1 &= 3 \times 10^{16} \text{ cm}^{-3} & d_2 &= 5 \text{ } \mu\text{m} \\ N_2 &= 2 \times 10^{14} \text{ cm}^{-3} & d_3 &= 0.3 \text{ } \mu\text{m} \end{aligned}$$

then $Z = 0.38 \text{ } \mu\text{m}$ and $d_z = 0.23 \text{ } \mu\text{m}$. From the point of view of the clock voltage the device behaves as a surface device with an oxide thickness of $0.23 \text{ } \mu\text{m}$. While, from the point of view of charge transfer it roughly behaves as a bulk device where all the charge is transferred at a depth of $B(\frac{\epsilon_1}{\epsilon_2}) d_1 = 4.8 \text{ } \mu\text{m}$. (see eq. 's (2.11) and (2.12)). The clock voltage needed for the given example is

$$\hat{V} = V_s + V_e = (5 + 6.4) \text{ volts}$$

For the profiled PCCD where we have only bulk transport it is not required to have an oxide layer. Schottky barrier or PN-junctions can be used. A clock voltage of 6.4 volts would then be sufficient. Which very nearly equals the clock voltage for the surface mode of operation for $0.1 \text{ } \mu\text{m}$ oxide thickness. Thus the profiled PCCD combines high charge handling capacity, freedom of surface states, at high transfer speeds.

2.1.3. The transfer of small charge fractions

The transfer inefficiency of small charge fractions for all the

operation modes of the SF-type PCCD can be written [5] as

$$\epsilon = \exp\left[-\frac{t}{\tau_s}\right] \quad (2.22)$$

where

$$\tau_s = \frac{4}{\pi^2} \frac{qL^2}{kT\mu} \approx \frac{4}{\pi^2} \frac{40L^2}{\mu} \quad (2.23)$$

This time constant is responsible for the relative slow transfer of the last charge fraction. A strongly decreased time constant for this last fraction will give a large improvement in transferspeed. Such a reduced time constant will be found for the externally-induced-field type.

2.2 Externally-induced-field type

Now L and d_2 are of the same order of magnitude. The driftfields (fringing fields) induced by externally applied potentials become very important, especially for the transfer of the last charge fraction. When there is no mobile charge in the device the potentials very near to the transferring electrode will be determined by that electrode so only a small driftfield may be expected. Deeper in the bulk the potential becomes more dependent on the potentials of the neighbouring electrodes so larger drift fields will exist there [4], [8], [9]. As a function of X (transfer direction) at $X = \frac{L}{2}$ a minimum for the drift field, below the transferring gate, is found. The drift field as a function of the depth, Y , for $X = \frac{L}{2}$, is given in fig. 9 [8]. A maximum for Y , (saddle point) of $E = \frac{V}{2L}$, is found at a depth of $Y \approx \frac{L}{2}$. When the last fraction is transferred at a depth around $\frac{L}{2}$ we will have a very short transfertime leading to high transferefficiencies (complete transfer) at high clock rates. This situation will occur in the homogeneously doped layer PCCD for bulk-mode operation and in the profiled PCCD, which has at the same time a good charge handling capacity.

In the profiled PCCD the main part of the charge is very near to its electrode. The charge packet will mainly be transferred by self-induced fields, while the last

fraction is driven further into the layer where much higher driftfields exist. The fractional charge with time will then be characterized by graph 4 of fig. 5 [10]. The transferefficiency will only be limited by bulkcenters.

For the transfer of a small fraction with the same boundary conditions at $X=0$ and $X=L$ it is possible to write [11]

$$\epsilon = \exp\left[-\frac{t}{\tau_e}\right] \quad (2.24)$$

$$t^{-1} = \frac{-1}{\tau_e \log \epsilon} \quad (2.25)$$

where
$$\tau_e = \frac{4}{\pi^2} \frac{L}{E\mu} \quad (2.26)$$

For $E = \frac{V}{2L}$ with $V = 5$ volt

$$\frac{\tau_s}{\tau_e} = \frac{qV}{2kT} \approx 100 \quad (2.27)$$

An improvement of two orders of magnitude for the EF-time constant, in comparison to the diffusion time constant for the SF-type. The inverse transfertime shown by eq. (2.25) for a given transferefficiency can be seen as a minimum upperbound. When we consider the charge transfer at a depth of about $\frac{L}{2}$ as "surf riding" caused by a traveling wave then the maximum upperbound is found by

$$t^{-1} = \frac{\mu V}{2L^2} \approx \frac{0.4}{\tau_e} \quad (2.28)$$

3. Experimental results and discussion

The first experimental results have been obtained with a SF-type PCCD with a substrate dope level of $N_a = 2 \times 10^{16} \text{ cm}^{-3}$ homogeneously doped epi-layer $N_d = 4 \times 10^{14} \text{ cm}^{-3}$ epi-layer thickness $d_2 = 6.8 \mu\text{m}$ oxide thickness $d_1 = 0.12 \mu\text{m}$ ϕ , Al electrodes length $L = 50 \mu\text{m}$ gap $G = 10 \mu\text{m}$

The experimental result of this device for one transfer has been given in [4] by which the factor B (eq. (2.14)) has been verified. A low frequency transferinefficiency of $\mathcal{E} = 1\%$ per transfer up to about 3.5 MHz and $\mathcal{E} \approx 5\%$ at 10 MHz was measured. The device was driven in the surface+bulk mode. Our low frequency transferinefficiency qualitatively agrees with that, obtained from extrapolation of the results given in [2].

To eliminate the influence of the electrode gaps on the transferefficiency, a four phase EF-type PCCD provided with a two layer metallization of aluminium and polycrystalline silicon electrodes on a homogeneously doped N-type epitaxial layer was made (fig. 10). The data of the dope levels and geometry are:

substrate dope level $N = 6 \times 10^{14} \text{ cm}^{-3}$
 epi-layer dope level $N_d^a = 6 \times 10^{14} \text{ cm}^{-3}$
 epi-layer thickness $d_2 = 4.5 \mu\text{m}$
 oxide thickness $d_1 = 0.15 \mu\text{m}$
 4ϕ , electrode length $L = 7.5 \mu\text{m}$
 number of electrodes 512

A transferinefficiency for bulk-transfer and real zero operation of $\mathcal{E} \approx 7 \times 10^{-5}$ per transfer has been measured in excess of 100 MHz. Real or fat zero operation had no influence on \mathcal{E} . Below some hundred kHz the \mathcal{E} became worse due to trapping effects. The worst response was found for a "one" after 250 or more "zero's" at 100 kHz, namely

$\mathcal{E}_1 \approx 3 \cdot 10^{-4}$ corresponding with an effective bulkcenterconcentration of about $2 \times 10^{11} \text{ cm}^{-3}$. Because of the much larger generation time constant of trapped electrons compared to the capture time constant, the transferefficiency of a "zero" after a large number of "one's" was always much better. At 100 kHz we found $\mathcal{E}_0 < 5 \cdot 10^{-5}$.

When we calculate the maximum frequency, for the given device from equations (2.25) and (2.26) with $V = 5$ volt, we find a 400 MHz clockfrequency for $\mathcal{E} = 10^{-4}$ 800 MHz clockfrequency for $\mathcal{E} = 10^{-2}$. From equation (2.28) it can be concluded that operation at clockfrequencies above 1GHz is possible.

Preliminary experiments measured up to 50 MHz on a profiled layer PCCD show transferinefficiencies of about 10^{-4} .

4. Conclusions

It has been shown, both by the aid of simplified theoretical models and by experiment, that the PCCD has a high charge handling capacity and is capable of transferring charge at high transferefficiencies ($> 99,99\%$) and at high operating frequencies (> 100 MHz).

In [12] more detailed considerations, calculated and experimental results, including the numerical method will be given.

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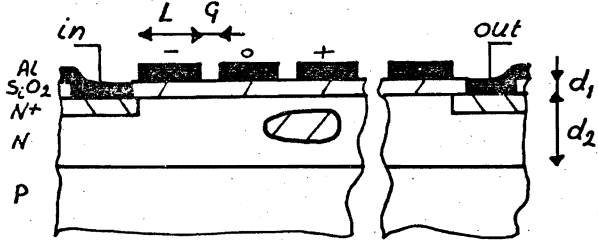


fig.1 homogeneously doped layer PCCD

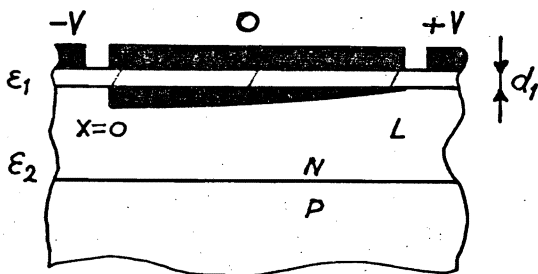


fig.2 surface mode operation

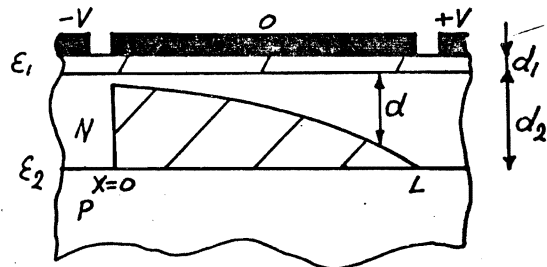


fig.3 bulk mode operation

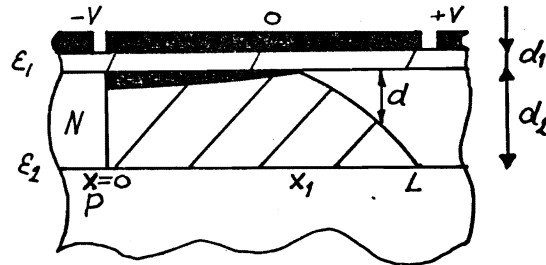


fig.4 surface + bulk mode operation

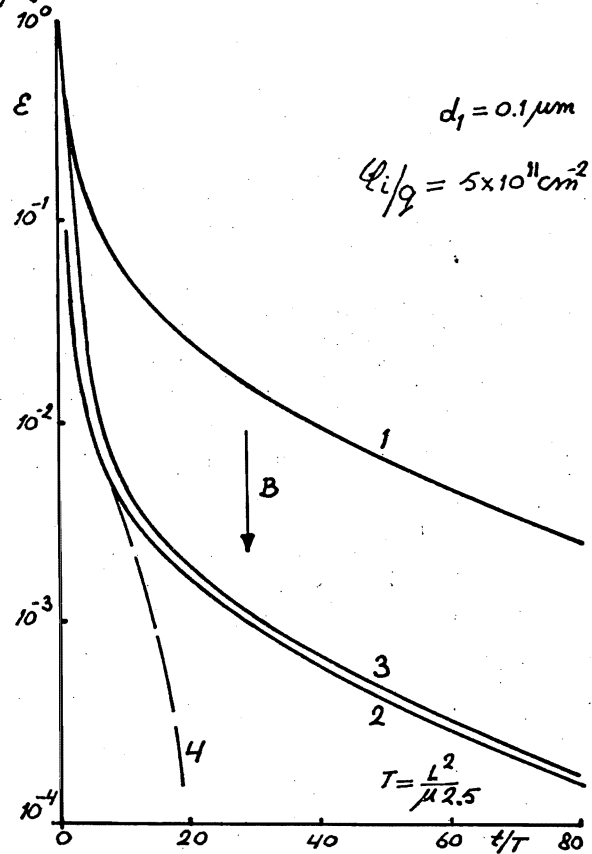


fig.5 fractional charge with time

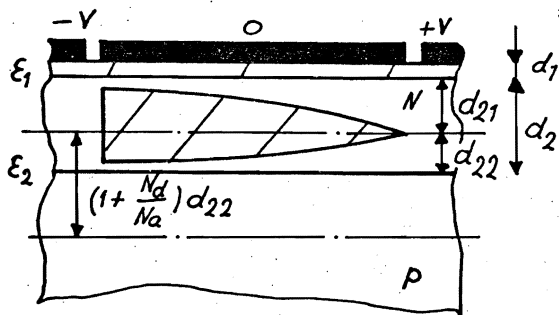


fig. 6 bulk mode operation

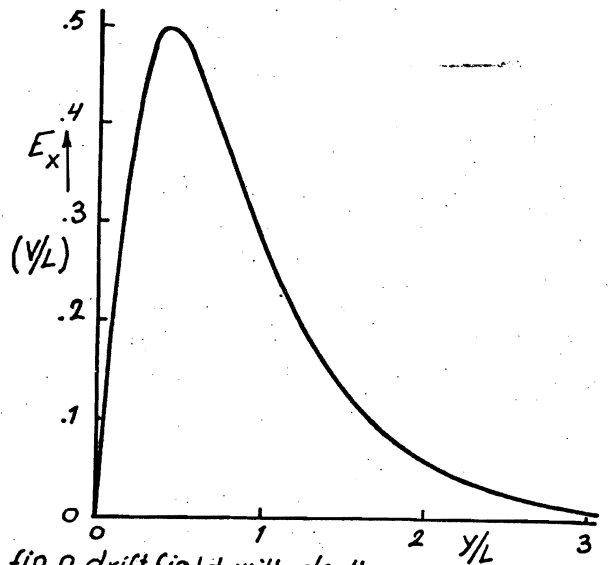


fig. 9 drift field with depth

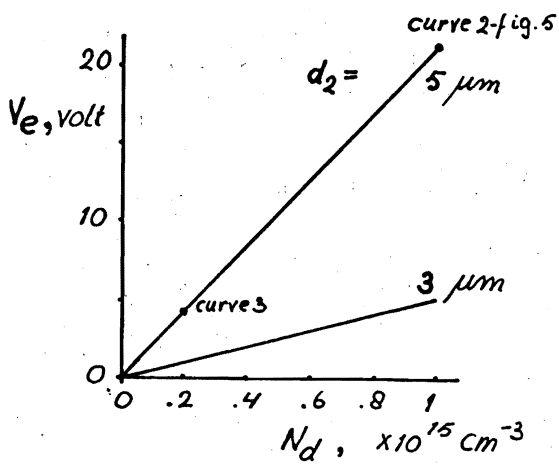


fig. 7 extra clock voltage with dope

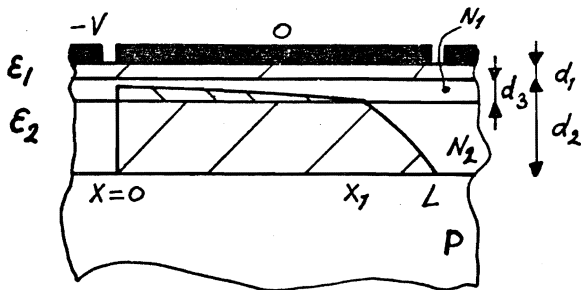


fig. 8 profiled PCCD

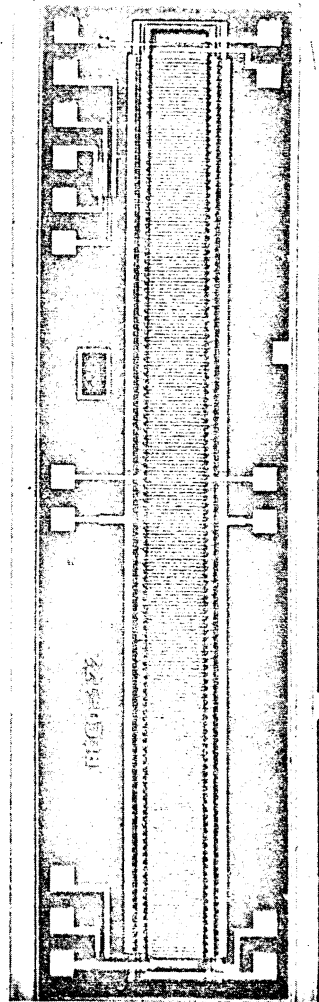


fig. 10 4φ experimental PCCD