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On the charge-handling capacity of epitaxial and ion-implanted GaAs buried channel charge-coupled devices ⁺

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Résumé. — La capacité de stockage en volume d'un D.T.C. GaAs a été étudiée à l'aide des solutions numériques des équations de Poisson 1-D et 2-D. Deux différentes technologies ont été envisagées : canal épitaxié avec grille Schottky et canal implanté avec grille M.I.S. Après avoir rappelé les conditions d'un stockage effectif en volume nous montrons qu'un D.T.C. à 3 phases et à grille Schottky permet d'atteindre la plus grande quantité de charges stockées. Une structure comportant un canal à double implant a été proposée pour éviter le contact des porteurs avec l'interface dans les D.T.C. à canal implanté. Pour les deux types de D.T.C., la capacité de stockage augmente quand la concentration du canal (ou la dose) ainsi que l'épaisseur du canal (ou la profondeur d'implant) sont réduits.

Abstract. — The charge-handling capacity of GaAs B.C.C.D.'s has been studied on the basis of the numerical solution of the 1-D and 2-D Poisson equations. Epitaxial and ion-implanted channels have been considered for two kinds of devices, respectively Schottky or M.I.S. gate B.C.C.D.'s. After having defined bulk storage conditions, we have showed that a 3-phase system and Schottky gate B.C.C.D. allow to store the more important signal-charge. A double implant channel structure is proposed to overcome the contact of the carriers with the interface in ion-implanted channel B.C.C.D. For both kinds of devices, the charge capacity increases when the channel doping concentration (or the dose) and when the channel thickness (or the implantation range) are reduced.

1. Introduction.

GaAs B.C.C.D.'s have been designed to be operated in the GHz transfer frequency range. Beside V.L.S.I. considerations, it is of importance to store and transfer large signal charge packets in order to minimize the effects of dark current generation, bulk trapping and to increase the sensitivity of the storage capacity of those devices.

The elementary cells under study are of two kinds :

- Schottky gates with an epitaxial n -type channel
- M.I.S. gates with an ion-implanted channel (the oxide gate is obtained through an anodic oxidation of the GaAs) [1, 2].

In the GHz range the more suited wave-form for the clock signals is a sinusoidal one ; 3 and 4-phase clocking schemes have been considered.

The Poisson equations (1-D and 2-D) have been

solved numerically in the n -channel and in the substrate to give at any grid point the values of the potential and of the signal charge density at thermal equilibrium. A finite difference method has been developed in an iterative routine [3].

For each kind of B.C.C.D., we shall determine the optimal values of the signal charge and we shall give its 2-D distribution in the device.

2. Conditions required for a bulk storage.

An elementary cell has been defined for the study of the charge storage : it comprises two half-gates G_1 and G_2 separated by a narrow gap (see Fig. 1b). The following conditions have to be fulfilled for both kinds of devices :

i) When the charges are stored under the biased gate G_2 , they must not overflow under the gate G_1 which is not biased (Fig. 1b), so the difference ΔV_M between the potential extrema under G_2 and G_1 respectively ($\Delta V_M = V_{\max 2} - V_{\max 1}$) must be positive (see Fig. 1c).

ii) The signal charge must be kept away from the

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Fig. 1a. — Potential distribution for the elementary cell.

Fig. 1b. — Signal charge location in the n-type channel.

Fig. 1c. — 1-D potential variation under the centre of the gates G_1 and G_2 showing $V_{\max 1}$, $V_{\max 2}$, the difference ΔV_M , the surface potential V_0 , and the difference $\Delta v = V_{\max 2} - V_0$.

interface to avoid trapping effects and a reduction of the carriers mobility. If V_0 is the value of the surface potential under G_2 , the difference between $V_{\max 2}$ and V_0 must be higher than a given value Δv .

iii) The breakdown of the oxide gate and the impact ionization of the n-type GaAs must be avoided : the normal electric field under the gate G_2 will be less than a limit value of 5×10^5 v/cm [4, 5].

3. Results concerning the epitaxial channel B.C.C.D.

3.1 1-D STUDY OF THE STORAGE CAPACITY. — The most significant parameter chosen for this study is the difference ΔV_M as defined in the previous section.

Its variation is represented in figures 2a and 2b as a function of the signal charge Q_{inj} (in C/m^2) for different values of the channel doping level N_D . The three above conditions for a bulk storage lead to define a region of operation related to a 3 or a 4-phase clocking scheme for which the clock swing is equal to 5 V (T.T.L. Comptability) For both devices, the channel thickness L is taken equal to $2 \mu m$ and the typical value of the p-type substrate doping level N_A is $10^{21}/m^3$. The M.I.S. gate C.C.D. has an oxide layer thickness t_{ox} equal to $0.1 \mu m$. The value of Δv has been taken equal to $0.5 v$ (Bulk storage).

First we can see that the 3-phase device gives values of ΔV_M higher than the 4-phase device and thus insures better storage conditions. Indeed, the difference between two adjacent gate voltages is 3.75 V for a 3-phase system whereas it is but 2.5 V for a 4-phase one. The values of ΔV_M are also higher for the Schottky-gate device (Fig. 2a) than for the M.I.S. device (Fig. 2b). For a given signal charge Q_{inj} , ΔV_M is all the more important as the doping level N_D is lower (but in any case upper than $3 \times 10^{21}/m^3$).

The influence of the channel thickness L on ΔV_M has also been studied. The results are represented in the figures 3a and 3b respectively related to the Schottky and the M.I.S. device. The signal charge Q_{inj} has been chosen equal to $2 \times 10^{-4} C/m^2$ for both figures. For a sake of simplicity, only the results obtained with a clock swing voltage due to a 4-phase clocking system have been given.

Once more, the storage capacity of Schottky gate devices is better than the one of M.I.S. devices.

The difference ΔV_M is a decreasing function of the channel thickness L . For a fixed value of L , ΔV_M also decreases when the channel doping increases. The same results have been obtained for a 3-phase clocking system.

The influence of the p-type layer doping level N_A has been tested : when it is varied from 10^{20} to 10^{22} atoms/ m^3 , very small variations of ΔV_M are obtained.

3.2 2-D RESULTS. — The 2-D Poisson equation has been solved numerically to verify the 1-D results for the two kinds of devices.

A theoretical Schottky structure has been defined : it comprises two $2.5 \mu m$ long half-gates separated by a gap of $0.5 \mu m$. We have used the following typical values : $L = 2 \mu m$, $N_D = 10^{22}/m^3$ and $N_A = 10^{21}/m^3$.

The figure 4a gives the potential distribution in the n-channel and in the substrate. The charges are located under the G_2 gate; their density corresponds to $10^{-4} C/m^2$ which gives $2.5 \times 10^{-10} C/m$ for a $2.5 \mu m$ half-gate.

Fig. 2a. — Schottky gate device : ΔV_M vs. Q_{inj} for a 3-phase and a 4-phase device. The parameter is the doping concentration N_D (3×10^{15} to $5 \times 10^{16}/\text{cm}^3$).

Fig. 2b. — Same curves for the M.I.S. gate device.

Fig. 3a. — Schottky gate device : ΔV_M vs. The channel thickness L for a 4-phase device. The parameter is the doping concentration N_D (2×10^{15} to $5 \times 10^{16}/\text{cm}^3$).

Fig. 3b. — Same curves for M.I.S. device.

Fig. 4a. — Schottky gate device : Potential distribution for a 4-phase device. The signal-charge is located under the gate G_2 .

Fig. 4b. — Signal-charge distribution : $Q_{inj} = 2.5 \times 10^{-10}$ C/m.

Fig. 4c. — Signal-charge distribution : $Q_{inj} = 1.5 \times 10^{-10}$ C/m.

In the gap, a potential extremum can be seen at the surface. This potential well diminishes and vanishes completely near the potential maxima in the bulk of the n-channel.

The signal-charge distribution has been represented (Fig. 4b) in a structure comprising two half-gates surrounding a gate. The signal-charge spreads totally into the two gaps and even overflows slightly under the two neighbouring half-gates.

When this signal charge Q_{inj} is reduced to 0.6×10^{-4} C/m² (1.5×10^{10} C/m), its location is better defined under the G_1 gate and no more overflows under the other gates. This situation has been represented in figure 4c.

These results could have been predicted for these Schottky gate devices by using the ΔV_M variations given in figure 2a.

For an M.I.S. devices, the same tendency has been found and we could verify that the ΔV_M values are always lower than for a Schottky-gate device under the same conditions and for the same typical values.

The structure under study has been improved to take into account two technological factors defining

other boundary conditions in the gaps :

- i) the presence of an Al_2O_3 layer in the gaps;
- ii) the overlapping of two adjacent gates.

These two modifications have not lead to results showing major variations about the charge locations with respect to those obtained with the more simple initial M.I.S. gate structure.

The influence of the gap width has been shown. This study of the edge effects requires necessarily the solution of the 2-D Poisson equation. When the gap width is reduced to $0.1 \mu m$, the potential distribution is modified at the interface, in the gap between the two half-gates (Fig. 5a). But the main modification can be seen on the charge distribution : for the signal-charge of 1.5×10^{-10} C/m, used previously (see Fig. 5b), the gaps are entirely occupied and a more important overflow takes place. This would impose a reduction of the signal-charge if a precise location is required before the transfer.

These results are detailed in a paper [6] where the influence of the gap width on the charge transfer is detailed.

Fig. 5a. — M.I.S. gate device : Potential distribution with a narrow gap of 0.1μ .

Fig. 5b. — Signal-charge distribution $Q_{inj} = 1.5 \times 10^{-10}$ C/m.

4. Study of the charge storage in an ion-implanted channel B.C.C.D.

4.1 1-D RESULTS. — The study of the ion-implanted channel device has been performed with the aid of a mathematical model of the impurity distribution (L.S.S. theory). We assume that all the implanted ions are electrically activated (as the result of an ideal annealing).

As for the epitaxial channel, we have reported the variation of ΔV_M as a function of the signal-charge Q_{inj} : the difference ΔV_M has been found to be a decreasing function of Q_{inj} (see Fig. 6). The upper condition limiting the implant dose is now $\Delta v = V_{max2} - V_0 = 0.1$ v. The implant range R_p is $0.5 \mu m$ and the straggle is $0.18 \mu m$. We find again that higher values of ΔV_M are obtained by using a 3-phase clocking system. For a given signal-charge Q_{inj} , the dose has to be reduced in order to keep satisfactory values of ΔV_M .

We have also reported the variation of ΔV_M as a function of R_p (similar to L in figure 3b). For a dose varying between 1.2 and 3×10^{12} at/cm², ΔV_M decreases when R_p varies from 0.2 to $0.8 \mu m$. For a given value of R_p , reducing the dose improves the values of ΔV_M (see Fig. 7).

The semi-insulating substrate acts as p-type layer with an equivalent doping concentration N_A of $7.5 \times 10^{21}/m^3$; this value was kept a constant for all the calculations.

From the curves given in figures 6 and 7, we have deduced typical values for Q_{inj} , R_p and the dose.

In figure 8, we give the corresponding impurity concentration in the channel (in arbitrary units) and the location of the signal charge Q . The resulting 1-D potential has been plotted.

For these typical values, the signal-charges are in contact with the oxide interface which is not in agreement with a real bulk operation of the device as it was defined in section 2.

4.2 2-D RESULTS. — This 2-D calculation gives the location of the signal-charge in the ion-implanted channel (see Fig. 9). The contact of the charge with the gate oxide which had been predicted with the aid of the 1-D calculation (Fig. 8) is verified. This situation cannot be satisfactory on the basis of the operating constraints defined in the upper sections.

4.3 DOUBLE IMPLANT-CHANNEL DEVICE. — To overcome the above drawback, a technological solution has been proposed: it consists in performing a second

Fig. 6. — Ion-implanted channel B.C.C.D.: ΔV_M vs. Q_{inj} for a 3 and a 4-phase system. The parameter is the dose varying from 1 to 3×10^{12} at/cm².

Fig. 7. — Ion-implanted channel B.C.C.D. : ΔV_M vs. the range R_p for a 4-phase device.

Fig. 8. — 1-D results : Impurity concentration in the channel (a). Signal charge location (b) showing the contact with the oxide surface and the resulting potential distribution (c).

Fig. 9. — 2-D signal charge distribution in the ion-implanted channel : the contact of the signal charge with the oxide surface is confirmed.

implant with a range centred on the oxide-GaAs interface and a dose much less ($\neq 1/10$) than the one of the main implant. The resulting impurity distribution is given in figure 10.

The 1-D Poisson equation is then solved and yields the signal charge distribution : no more contact of the charge with the interface can be seen (see Fig. 10).

As a verification we have solved the corresponding 2-D Poisson equation : the results confirm the 1-D calculations. In figure 11, we have reported the signal-charge location : this second implant has corrected the effect of the main implant and now the charges are located in the bulk of the resulting implanted channel.

Fig. 10. — Description of the double implant device showing : the main implant « a », the second implant « b », the resulting implanted impurity distribution and the potential variation.

Fig. 11. — 2-D signal distribution in the double implanted device showing that the carriers are no more in contact with the oxide surface.

5. Concluding remarks.

We have studied Schottky barrier C.C.D. and M.I.S. barrier C.D. on GaAs. For both kinds of devices, the storage capacity is all the more important as the doping level (or the dose) and as the channel thickness (or the range) are reduced. These variations of ΔV_M have been found by the solutions of the 1-D and 2-D Poisson equations : they are quite opposite to intuitive

solutions which would have consisted in increasing the doping level and the channel thickness to store more signal-charges.

The Schottky gate devices insure a higher storage capacity than the M.I.S. gate devices under the same operating conditions but in the present state of the GaAs C.C.D. technologies this is not a sufficient criterion to enable choosing between these two kinds of devices. Anyway, the drawback associated with the ion-implanted channel can be overcome by performing a second implant and realizing a resulting implanted channel which could store and transfer carriers far enough from the interface.

A 3-phase clocking scheme seems to be a better solution than a 4-phase one because it leads to higher clock swings and hence to deeper potential wells more likely to store important signal-charge [7].

Finally, the 1-D results have been verified and completed by the solutions of the 2-D Poisson equation giving the exact 2-D charge location in the channel and the potential distribution taking into account the edge effects due to the gap width and the neighbouring gate potentials.

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