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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 de l'interface 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 $G_1$ (Fig. 1b), so the difference $\Delta V_M$ 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
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 $\Delta V_M$ 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 $\Delta V$ has been taken equal to 0.5 V (Bulk storage).

First we can see that the 3-phase device gives values of $\Delta V_M$ 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 $\Delta V_M$ are also higher for the Schottky-gate device (Fig. 2a) than for the M.I.S. device (Fig. 2b).

For a given signal charge $Q_{inj}$, $\Delta V_M$ is all the more important as the doping level $N_D$ is lower (but in any case upper than $3 \times 10^{21}$/m$^3$).

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, $N_D = 10^{21}$/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: $\Delta V_M$ vs. $Q_{inj}$ for a 3-phase and a 4-phase device. The parameter is the doping concentration $N_D (3 \times 10^{15}$ to $5 \times 10^{16}/\text{cm}^3)$.

Fig. 2b. — Same curves for the M.I.S. gate device.
Fig. 3a. — Schottky gate device: $\Delta V_M$ vs. The channel thickness $L$ for a 4-phase device. The parameter is the doping concentration $N_D$ ($2 \times 10^{15}$ to $5 \times 10^{16}$/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 $G_2$. 
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 $0.6 \times 10^{-4}$ C/m$^2$ ($1.5 \times 10^{10}$ 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 $\Delta V_M$ variations given in figure 2a.

For an M.I.S. devices, the same tendency has been found and we could verify that the $\Delta V_M$ 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$_2$O$_3$ 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 µm, 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 $1.5 \times 10^{-10}$ 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.
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 $\Delta V_M$ as a function of the signal-charge $Q_{inj}$; the difference $\Delta V_M$ has been found to be a decreasing function of $Q_{inj}$ (see Fig. 6). The upper condition limiting the implant dose is now $\Delta u = V_{max2} - V_0 = 0.1$ 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 $\Delta V_M$ 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 $\Delta V_M$.

We have also reported the variation of $\Delta V_M$ as a function of $R_p$ (similar to $L$ in figure 3b). For a dose varying between 1.2 and $3 \times 10^{12}$ at/cm$^2$, $\Delta V_M$ 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 $\Delta V_M$ (see Fig. 7).

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

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.

Fig. 6. — Ion-implanted channel B.C.C.D.: $\Delta V_M$ vs. $Q_{inj}$ for a 3 an a 4-phase system. The parameter is the dose varying from $1 \times 10^{12}$ to $3 \times 10^{12}$ at/cm$^2$. 
Fig. 7. — Ion-implanted channel B.C.C.D. : $\Delta V_M$ vs. the range $R_p$ for a 4-phase device.

implant with a range centred on the oxide-GaAs interface and a dose much less ($\approx 1/10$) 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. 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.

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.
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 $\Delta V_m$ 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 solutions 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.

References