Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 95-98 **B-3-7**

A New Interpretation of the Orientation Effect in GaAs MESFET's

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This paper presents a new explanation of the orientation effect of self-aligned WSix GaAs MESFET's by taking the different channel- substrate interfaces formed in [011] and [01$\bar{1}$] direction due to the piezoelectric charges, and the velocity saturation properties in GaAs MESFET's into account. The predicted results are in agreement with measurement data.

1. INTRODUCTION

To improve the switching speed of GaAs LSI's, it is essential to increase the transconductance of the FET's by reducing the gate lengths. However, as the gate length is reduced to 2.0 um or less, it was found that the electrical characteristics of the GaAs MESFET's depend on the orientations of the FET's on the substrates[1-2]. The FET's oriented in [011] and [01$\bar{1}$] directions on (100) substrate exhibit different threshold voltages. A stress-enhanced preferential diffusion model[1-3] and a piezoelectric effect model[4-5] have been proposed to explain the orientation effect. It has been shown that the piezoelectric effect was the main cause of orientation [4-9].

For CVD Si_3N_4 overlayers, reported by Lee etal[1], threshold voltage varied substantially with the gate length for orientation in the [01$\bar{1}$] direction, but it was nearly independent of the gate length for the [011] direction. For CVD SiO_2 overlayers, however, reported by Yokoyama etal[2], the threshold voltage shifts were of opposite sign to that reported by Lee etal for the [011] and [01$\bar{1}$] orientations. Ohnishi etal[6] confirmed that SiO_2 films on GaAs are in compression, while Si_3N_4 films are in tension, and resolved the problem of the conflicting data by Lee[1] and Yokoyama[2].

According to the piezoelectric effect model[4], the curves of the threshold voltage shifts should have the same magnitude and opposite sign of bending for the FET's in [011] and [01$\bar{1}$] directions. But, as mentioned above, the experimental results are that the threhold voltage is less dependent on the gate length for the FET's in one direction than in the perpendicular direction. The reason for asymmetric inverse shifts of the threshold voltages remains unclear. On the basis of the piezoelectric effect model, we propose a new interpretation of the orientation effect. The predicted results agree with the experimental data. This provides a clear explanation of the asymmetric inverse shifts of the threshold voltage in these two perpendicular directions.

2. INTERPRETATION

(1) Piezoelectric charge density

Fig.1 shows the cross-section view of the WSix gate self-aligned MESFET used in this analysis, with the coordinate system for calculation.

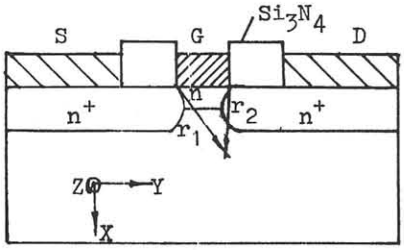

Fig.1. Cross section of self-aligned WSix-gate GaAs MESFET's with coordinate system for calculating piezoelectric charge distribution.

The piezoelectric charge density is given by[4]

$$\rho_{pz}(x,y) = \frac{2d_{14}\sigma_f d_f}{\pi}\left[\frac{y_1 x((4-\gamma)y_1^2-(2+\gamma)x^2)}{r_1^6} - \frac{y_2 x((4-\gamma)y_2^2-(2+\gamma)x^2)}{r_2^6}\right] \quad (1)$$

where γ=0.23, is the Poission's ratio of GaAs, $d_{14}=2.60\times10^{-17}$C/dyn =163electrons/dyn, piezoelectric constant, which is positive for [011] FET's and negative for [01$\bar{1}$] FET's, σ_f is the stress, which is defined as positive when the FET channel region is forced to expand, d_f the dielectric overlayer thickness, and L is the gate length.

(2) The velocity saturation properties

According to the velocity saturation model in GaAs FET's[10], there are two regions in the FET channel: The constant mobility region L_1 and The electron velocity saturation region L_2. Under the low-field condition, the channel is pinched off first at $Y_1=L_1$, $Y_2=-L_2$. On the basis of the data in [10], L_1 is approximately equal to 3L/4. Hence, we calculate the V_{th} shift at L_1=3L/4, approximately, not as [4] at the center of the gate.

(3) The threshold voltage shift

The piezoelectric charge density alters the origin doping density, resulting in the threshold shift. As shown by Onodera etal[7], the effective channel thickness, which has a logarithmic dependence on the space charge density on both sides of the channel-substrate interface, is modified by the piezoelectric charge density. It may be suggested that when the piezoelectric charge is negative near the interface, there exists a one sided p-n-junction-like interface formed on the back of the channel. For $\rho_{pz}<0$, the depletion layer width of the channel side at the channel-substrate becomes a little wider.

The threshold voltage in GaAs MESFET's can be written as

$$V_{th} = \Phi_B - \frac{q}{\varepsilon_s}\int_0^W x\, N_D(x)\, dx \quad (2)$$

where q is the electron charge, ϕ_B is the Schottky barrier height, ε_s is the dielectric constant, W is the effective channel thickness without the piezoelectric charge. $N_D(x)$ is the implanted donor density.

Due to the piezoelectric charge density modulation, the threshold voltage becomes

$$V'_{th} = \Phi_B - \frac{q}{\varepsilon_s}\int_0^{W_t} x(N_D(x)+\rho_{pz}(x)/q)\,dx \quad (3)$$

where Wt is the effective channel thickness with the piezoelectric charge.

For the negative piezoelectric charge density, the threshold voltage shift can be expressed as

$$\Delta V_{th} = V_{th}' - V_{th} = -\frac{q}{\varepsilon_s}\int_0^{W_t} x\,(N_D(x)+\rho_{pz}(x)/q)dx + \frac{q}{\varepsilon_s}\int_0^{W_t} xN_D(x)dx + \frac{q}{\varepsilon_s}\int_{W_t}^{W} xN_D(x)dx$$

$$= -\frac{1}{\varepsilon_s}\int_0^{W_t} x\rho_{pz}(x)dx + \frac{q}{\varepsilon}\int_{W_t}^{W} xN_D(x)dx \qquad (4)$$

since the piezoelectric charge density $\rho_{pz}(x)$ at x=Wt equals approximately $qN_D(x)$ at x=Wt [7], and W-Wt is very small, we obtain by taking the sign of the charge density into account.

$$-\frac{q}{\varepsilon_s}\int_{W_t}^{W} xN_D(x)dx \simeq \frac{1}{\varepsilon_s}\int_{W_t}^{W} x\rho_{pz}(x)dx \qquad (5)$$

Combining Eqs.(4) and (5), we have

$$\Delta V_{th} = -\frac{1}{\varepsilon_s}\int_0^{W} x\,\rho_{pz}(x)dx$$

$$= -\frac{d_{14}\sigma_f d_f}{2\pi\,\varepsilon_s}\left[(1+2\gamma)(\text{arctg}A+\text{arctg}B) - \frac{A[1+2\gamma+(7+2\gamma)A]^2}{(1+A^2)^2} - \frac{B[1+2\gamma+(7+2\gamma)B]^2}{(1+B^2)^2}\right] \qquad (6)$$

where A=4W/3L, B=4W/L.

It may also be suggested that when the piezoelectric charge is positive, there is a n-n⁻ junction-like channel-substrate interface. Because of the positive charge in the substrate, an additional carrier distribution is formed below the channel, which gives rise to the substrate current. For the positive piezoelectric charge, the effective channel may spread over the part of substrate. The threshold voltage shift can be expressed as

$$\Delta V_{th} = -\frac{q}{\varepsilon_s}\int_0^{W} x\,(N_D(x)+\rho_{pz}(x)/q)dx - \frac{q}{\varepsilon}\int_{W}^{W_t} x(N_D(x)+\rho_{pz}(x)/q)dx + \frac{q}{\varepsilon_s}\int_0^{W} xN_D(x)dx$$

$$= -\frac{1}{\varepsilon_s}\int_0^{W_t} x\rho_{pz}(x)dx - \frac{q}{\varepsilon_s}\int_{W}^{W_t} xN_D(x)dx \qquad (7)$$

Here are two methods to calculate Eq.(7). In the first method, we calculate the threshold voltage shift in the same way as Eq.(5), taking the same sign of piezoelectric charge density as that of doping density into account. It can be obtained

$$\Delta V_{th} = -\frac{1}{\varepsilon_s}\int_0^{W} x\rho_{pz}(x)dx - \frac{2}{\varepsilon_s}\int_{W}^{W_t} x\rho_{pz}(x)dx \qquad (8)$$

In the second method, Eq.(7) can be expressed as

$$\Delta V_{th} = -\frac{1}{\varepsilon_s}\int_0^{W_t} x\rho_{pz}(x)dx - \frac{q}{\varepsilon_s} W_t N_D(W_t)(W_t - W) \qquad (9)$$

This is similar to Asbeck etal's result[4]. The depletion region variation due to the piezoelectric charge may approximately be determined from perturbative solutions to the one-dimensional Possion equation.

It can obviously be seen from Eqs.(6) and (8) that the sign of the piezoelectric charge density gives rise to the asymmetric inverse shifts of the threshold voltage in GaAs MESFET's, and the threshold voltage shift with the positive piezoelectric charge is bigger than that with the negative for the same magnitude of the piezoelectric charge density.

3.COMPARISON WITH EXPERIMENTS

GaAs MESFET's were fabricated using a self-aligned WSix gate process. The n channel and n regions were obtained by Si implantation at an energy of 50kev with a dosage of $6\times10^{12}cm^{-2}$, and 80kev with a dosage of $4\times10^{13}cm^{-2}$, respectively. Annealing was made at 800°C for 15min for the n channel and at 750°C for 10min for the n^+ regions. The dielectric overlayer is PECVD

Si_3N_4. Si_3N_4 films here are in tension by X-ray diffraction measurements. The details about our experiments are to be published.

Fig.2 showns comparison of the results in the literature[4] with the calculated results (with $\sigma_f d_f$=1x10^5dyn/cm, W=0.17um, L=1.0um, Wt=0.20um). On the other hand, for compressive overlayers, the predicted results are opposite to the above for [011] and [01$\bar{1}$] orientation. This is qualitatively in agreement with Yokoyama etal' results[2], where the SiO_2 dielectric overlayers were in compression.Because the n^+ dopants laterally diffused into the active channel, this may be operative which may be big enough to cancel the piezoelectric shifts predicted here for [01$\bar{1}$]-oriented FET's with the compressive overlayers, and for [011]-oriented FET's with

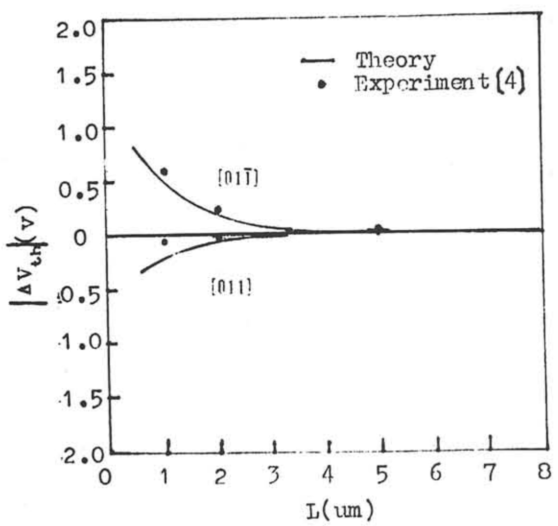

Fig.2. Comparison of the experiments in the literature [4] with the calculated results.

the tensile overlayers. For [01$\bar{1}$]-oriented FET's, the piezoelectric charge is positive. There exists a n-n^- junction formed at the channel-substrate interface. Under this condition, the greater threshold voltage shifts are predicted. For [011]-oriented FET's, the piezoelecric charge negative, there is a p-n junction. The threshold voltage shifts are small. The predicted results agree with experimental data. It can be seen that the threshold voltage shift of FET' in [01$\bar{1}$] direction than that of FET's in [011] direction.

4.CONCLUSIONS

The results presented here suggest that the sign of piezoelectric charges plays a role in the explanation of the asmmetric inverse shifts of GaAs MESFET's threshold voltages. For positive piezoelectric charges, the n-n^- junction is formed at the channel-substrate interface, and the threshold voltage shifts are greater than for negative piezoelectric charges which result in the p-n-junction formed at the channel-substrate interface.

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