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The Effect of Substrate Purity on Short-Channel Effects of GaAs MESFET's

Hiroshi Nakamura, Masanori Tsunotani, Yoshiaki Sano, Toshio Nonaka, Toshimasa Ishida and Katsuzo Kaminishi

Research Laboratory, Oki Electric Industry Co., Ltd.
550-5 Higashiasakawa, Hachioji, Tokyo 193 Japan

The effect of substrate purity on short-channel effects of GaAs MESFET's is discussed. As a substrate with high purity, an MOCVD-grown undoped buffer layer was used, and as a substrate with low purity, the substrate implanted with carbon and/or oxigen ions was used. The threshold voltage strongly changed when C and/or O ions were implanted beneath the channel. The short-channel effects were fairly supressed when the substrate was "impure".

1. Introduction

Recent development in self-alignment GaAs MESFET processing technologies has enabled the fabricaton of high speed GaAs LSI's. To improve the switching speed of GaAs MESFET's further, the reduction of gate length is quite effective. However, as the gate length is decreased, many harmful effects appear, especially in n^+ ion implanted self-aligned FET's. The threshold voltage (V_{th}) shifts towards negative, sub-threshold current increases, and the drain conductance increases. These effects are called short-channel effects. To overcome these effects, various works have been already reported. The established points effective to reduce short channel effects in self-aligned MESFET's are as follows:

1)To decrease the thickness of active layer[1),
2)To decrease the thickness of n^+ layer[2,3)],
3)To separate gate metal and n^+ implanted region[4)].

However, it is sometimes observed that the degree of short-channel effects differs from wafer to wafer even though the processing conditions are the same. These phenomena are thought to be caused by the difference in the purity of semi-insulating substrate. In Si n-channel MOSFET, it is well known that short-channel effects are strongly affected by the acceptor concentration of the substrate[5)]. In this paper, the effect of substrate purity on short-channel effects of GaAs MESFET is studied experimentally for the first time. An MOCVD grown undoped buffer layer was used as the substrate with high purity, and the layer in which carbon and/or oxigen were implanted was used as the substrate with low purity.

2. Experimental

By using low-pressure MOCVD system, high purity GaAs layer can be grown. The residual impurity concentration (N_d+N_a) is estimated to be less than $1x10^{15}$ cm^{-3} because the electron mobility of the slightly n-type epitaxial layer at 77K exceeds 1x 10^5 $cm^2/V.s$. By adjusting the $[TMG]/[AsH_3]$ ratio, high resistivity layer of 2-3 µm thickness can be obtained. Because the carrier is completely depleted by the surface and/or interface built-in potential and surface leakage current is negligible, this MOCVD grown high resistivity layer can be successfully used as the substrate for ion implantation to make MESFET[6)]. This substrate (MO-substrate) is thought to be one of the purest substrates that are now available.

To make "impure" substrate, ^{12}C and/or ^{16}O ions were implanted into the MO-substrate. The ^{12}C ion and ^{16}O ion implantations were performed without a mask at energies of 80 keV and 100 keV with doses of more than $1x10^{12}$ cm^{-2}, respectively.

In these substrates, MESFET's with various gate lengths were fabricated using W-Al gate self-alignment process[3)]. The active layer was formed by ^{29}Si ion implantation at an energy of 60 keV with a

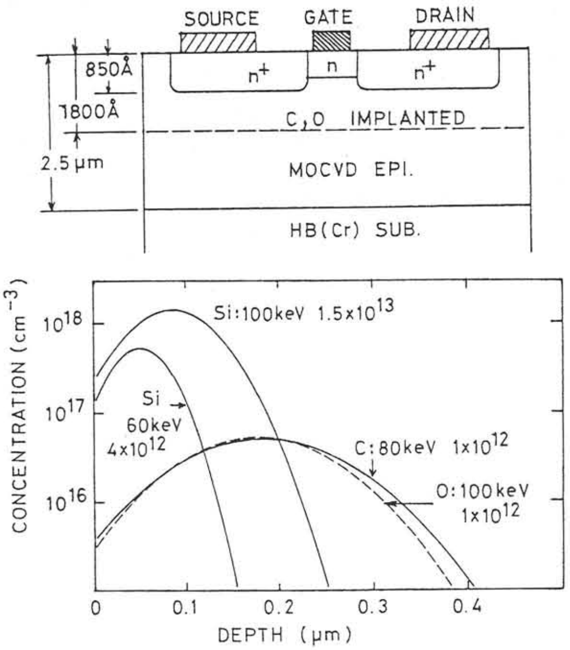


Fig.1 Cross-section of the MESFET and calculated as-implanted impurity profiles of silicon, carbon and oxigen.

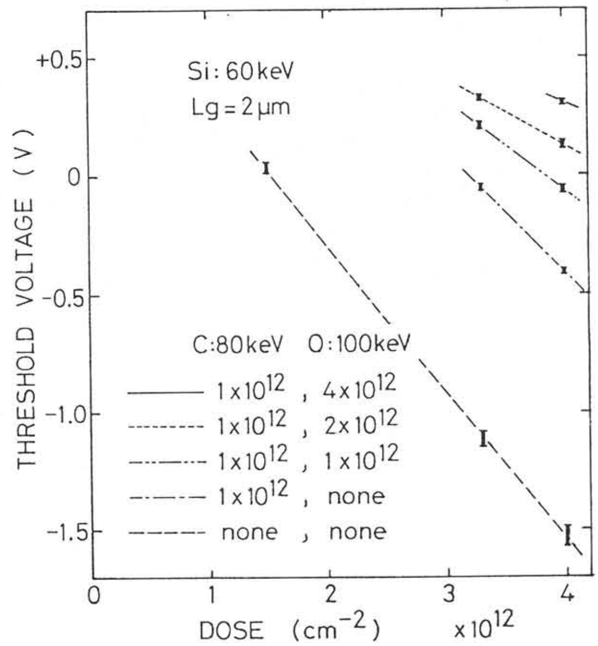


Fig.2 Dependence of V_{th} on Si doses using C and O doses as parmeters.

dose of $1.5x10^{12}$, $3.3x10^{12}$ or $4.0x10^{12}$ cm^{-2}. The ion implantation for n^+ layer with a gate mask metal was done by 100 keV ^{29}Si with a dose of $1.5x 10^{13}$ cm^{-2}. The direction of the gate was [011] (drain current flows parallel to [0$\bar{1}$1] direction) according to the definition of Ref.7. The annealing with an SiO_2 cap was done at 800°C for 20 min under AsH_3 + Ar atmosphere.

The cross-section of the device structure and the calculated depth profile of implanted ions (as implanted) are shown in Fig.1. The peak positions of implanted ^{12}C and ^{16}O ions are almost the same, and are far deeper than ^{29}Si profiles for active and n^+ regions. The V_{th} of the MESFET was determined by the relation between $(I_d)^{1/2}$ and V_g.

3. Results

3.1 Threshold voltage

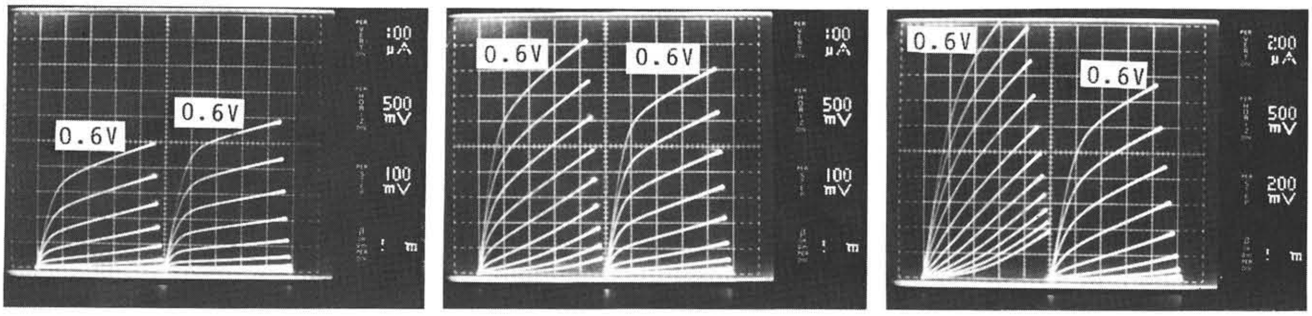
The relation between V_{th} and dose of ^{29}Si implantation is shown in Fig.2 as a parameter of ^{12}C and/or ^{16}O doses. The gate length is 2.0 μm. As seen in this figure, the introduction of carbon ions beneath the channel strongly increases the V_{th}. The additional introduction of oxigen ions increases the V_{th} more. The amount of V_{th} shift is much larger than the value that one implanted carbon atom is assumed to compensate one Si atom.

The data shown in Fig.2 were measured within one wafer. The error bar in Fig.2 is 2σ of about 10 samples. The standard deviation (σ) of V_{th} are very small (15-30 meV) because MO-substrate has little residual impurities and dislocations . Fortunately, the V_{th} of the FET's of ($\phi Si=1.5x10^{12}$ cm^{-2}, $\phi C=\phi O=0$) and ($\phi Si=3.3x10^{12}$ cm^{-2}, $\phi C=1.0x10^{12}$ cm^{-2}, $\phi O=0$) are nearly the same. So, the FET properties of these two samples can be easily compared without the influence of V_{th} difference. In the following sections, we mainly deal with the difference between these two samples. We call these two FET's "pure" FET and "impure" FET, respectively, in this paper.

The surface or substrate leakage current of carbon and/or oxigen ion implanted substrate was negligible when ion implantation conditions were those written in Fig.2. When carbon ion implantation was performed at 80 keV with a dose of $1.0x 10^{13}$ cm^{-2}, however, the substrate was changed to p-type and leakage current was large.

3.2 Short-channel effects

Fig.3(a)-(c) show the static properties of "pure" FET's and "impure" FET's with 1.5 μm, 1.0 μm and 0.5 μm gate length. Gate widths are all 10 μm. Although the difference in the FET's with 1.5 μm gate length is small, the static property difference between two FET's becomes larger as the gate



"pure" FET "impure" FET
(a) L_g=1.5 µm

"pure" FET "impure" FET
(b) L_g=1.0 µm

"pure" FET "impure" FET
(c) L_g=0.5 µm

Fig.3 Difference in static properties between "pure" FET (the FET formed on "pure" substrate) and "impure" FET (the FET formed on "impure" substrate).

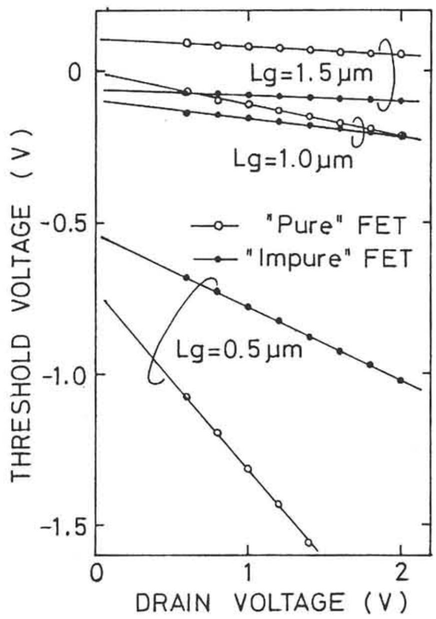


Fig.4 Dependence of V_{th} on drain voltage in "pure" and "impure" FET's with various gate length.

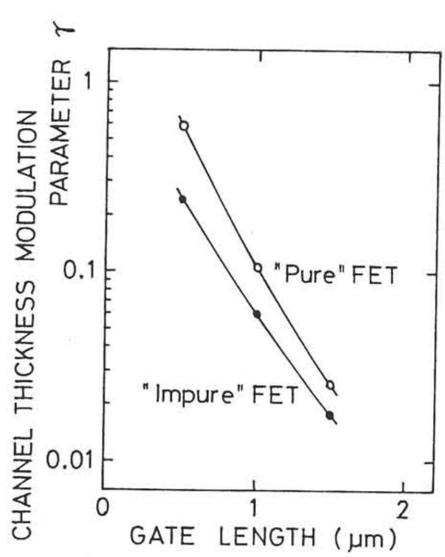


Fig.5 Dependence of channel thickness modulation parameter (the slope of Fig.4) on gate length.

length is decreased. Drain conductance and sub-threshold current are much increased in "pure" FET's.

Such a difference in static properties can be well expressed by the dependence of V_{th} on drain voltage (V_d). It is shown in Fig.4 as a parameter of gate length. The linearlity between V_{th} and V_d is excellent. So, the channel thickness modulation parameter (γ)[8] can be obtained from the slope of the lines. Fig.5 shows the dependence of γ on gate length. The γ in "pure" FET is about twice of that in "impure" FET. The ratio of γ between "pure" FET and "impure" FET increases as the gate length decreases.

Figure 6 shows the dependence of V_{th} on gate length. Two kinds of V_{th}, V_{th0} (V_{th} at V_d=0V) and V_{th1} (V_{th} at V_d=1V) are shown in this figure. The V_{th0} of "impure" FET is almost constant between gate length of 1.0 µm and 5.0 µm, whereas, the V_{th0} of "pure" FET differs between gate length of 1.0 µm and 1.5 µm. Moreover, the difference in V_{th} of "pure" FET between 0.5 µm gate and 5.0 µm gate is about twice of that of "impure" FET.

4. Discussion

The implanted carbon ions are thought to form shallow acceptors in GaAs crystal when annealed at high temperatures. However, the activation efficiency of carbon ions at 800°C annealing was reported to be very low[9]. So, it is difficult to assume that all implanted carbon ions form shallow acceptors. The fact that substrate leakage current was negligible at the carbon dose of $1x10^{12}$ cm^{-2} supports this consideration. However, as shown in

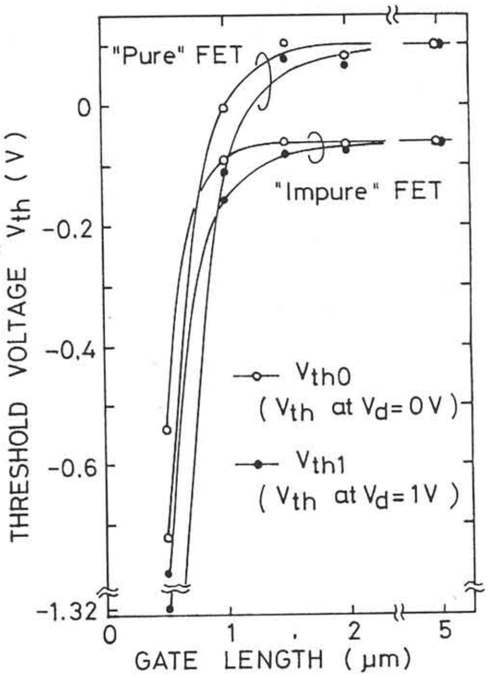


Fig.6 Dependences of V_{th0} and V_{th1} on gate length in "pure" and "impure" FET's.

Fig.2, small amount of implanted carbon ions strongly increases the V_{th}. Therefore, the carbon atoms which are not activated in the crystal are thought to play a major role. It is not clear wheather they are deep acceptors, deep donors or other deep levels. It is sure, however, that the purity of the substrate becomes lower when carbon ions are implanted.

The results of Fig.3 - 5 reveal that the current flowing beneath the channel (substrate current) is much supressed in "impure" FET's.

The Fermi levels of active layer is near the conduction band edge, and that of semi-insulating (S.I.) substrate is near the mid-gap. Therefore, the depletion layer exists between active layer and S.I. substrate. The width of depletion layer and the curvature of conduction band edge are determined by the total donor (shallow or deep) concentration of active layer and the total acceptor (shallow or deep) concentration of the substrate (N_{as}). If N_{as} is high, many part of the depletion layer lies in the active layer side, and the band bending beneath the channel is strong. On the contrary, if N_{as} is low, most of the depletion layer lies in the substrate side and the depletion layer width is large. The band bending beneath the channel is weak.

The difference in the depletion layer width in active layer side explains the experimental results of V_{th} difference (Fig.2), and the difference in the band bending beneath the channel explains the difference in substrate current.

Because the experimental results can be explained qualitatively by the difference in total acceptor concentration in the substrate, the main part of the implanted carbon ions which do not form shallow acceptors are thought to form deep acceptors. Furthermore, some part of implanted oxigen ions are also thought to form deep acceptors.

5. Conclusion

The static properties of two types of FET's were mainly compared in this paper. One is made in the high purity MO-substrate ("pure" FET), and the other is made in the carbon ion implanted MO-substrate ("impure" FET). Although the activation efficiency of implanted Si ions are small in the "impure" FET, the short-channel effects in the "impure" FET are weak.

From the results of this work, it can be concluded that the substrate must not be too pure in order to fabricate short-channel FET's. However, the ordinary available "impure" substrates do not have sufficient uniformity of impurity concentration. The uniformity of the amount of impurity strongly affects the V_{th} uniformity. Therefore, the substrate which is made by controlled doping of carbon and/or oxigen ions into high purity substrate is very advantageous to fabricate uniform and high performance short-channel FET's.

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