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Oxidation Using AFM and Subsequent Etching in Water of Inverted-Type δ-Doped HEMT

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Using an atomic force microscope, we have formed an oxide wire on a channel region of the inverted-type delta-doped high-electron-mobility transistor. In this time, we discovered that the oxide wire is etched in water, moreover that consequently the trench is formed. Applying this property, we have controlled the height of the potential barrier in the two-dimensional electron gas channel.

1. Introduction

An atomic force microscope (AFM) and a scanning tunneling microscope (STM), which have the possibility of an atomic-scale modification of the surface, are attractive tools for fabricating the nanometer-scale devices such as the single-electron devices. For example, Campbell *et al.*[1] fabricated side-gate Si field effect transistors (FETs); Minne *et al.*[2] fabricated a metal oxide semiconductor FET (MOSFET) on Si. Their approaches are based on selective oxidation of a Si surface using the AFM followed by pattern transfer through selective etching. On the other hand, Matsumoto *et al.*[3] have used the oxide wire which is formed in a Ti channel as the tunnel barrier of the metal-insulator-metal (MIM) diode which is the fundamental device for the single-electron transistor (SET).

Recently, we have succeeded in depleting a two-dimensional electron gas (2DEG) channel in the GaAs/AlGaAs delta-doped high-electron-mobility transistor (HEMT) using an oxide wire formed with the AFM.[4] In this time, we have formed the oxide wire on the inverted-type delta-doped HEMT for controlling the height of the potential barrier in the 2DEG channel.

2. Experiments and discussion

Figure 1 shows the selective oxidation procedure using the AFM. The oxide wire was formed by moving the conductive cantilever biased negatively to the sample. We considered the following two oxidation mechanisms. Natural oxidation is accelerated by the electric field applied between the cantilever and the sample so that the sample is positive relative to air,[5] which was supported by Ejiri *et al.* who oxidized Si using the AFM.[6,7] On the other hand, another possible oxidation mechanism is anodization through the moisture between the cantilever and the sample, which was supported by Sugimura *et al.* who oxidized Ti using the STM.[8,9] However, so far, we were not able to establish the exact oxidation mechanism.

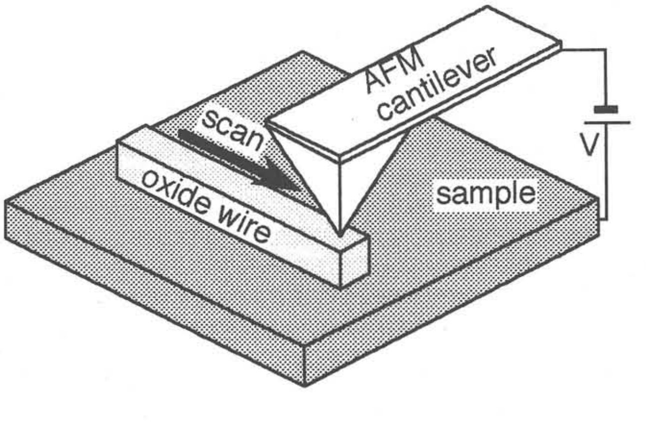
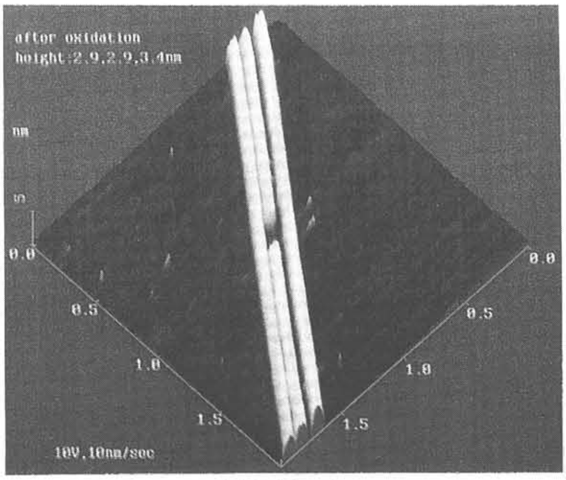
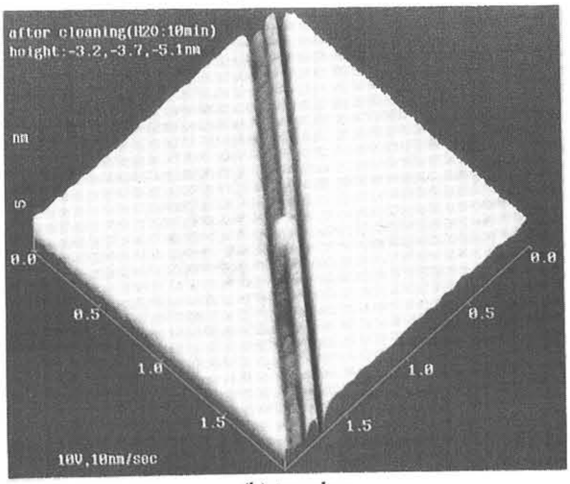


Fig. 1. Selective oxidation procedure using AFM.

Figure 2(a) shows the AFM image of the oxide wires formed with the applied voltage of 10 V at the scanning



(a) Oxide wires



(b) trenches

Fig. 2. AFM image of sample (a) before and (b) after stir in water for 10 minutes.

speed of 10 nm/s. We observed again the sample after the stir in water for 10 minutes; on that occasion, we discovered that trenches are formed just at the place where the oxide wires had existed, as shown in Fig. 2(b). It is obvious that the oxide wires dissolved in the water. We investigated the relation between the depth of the trench and the height of the oxide wire, as shown in Fig. 3. The negative sign of the y-

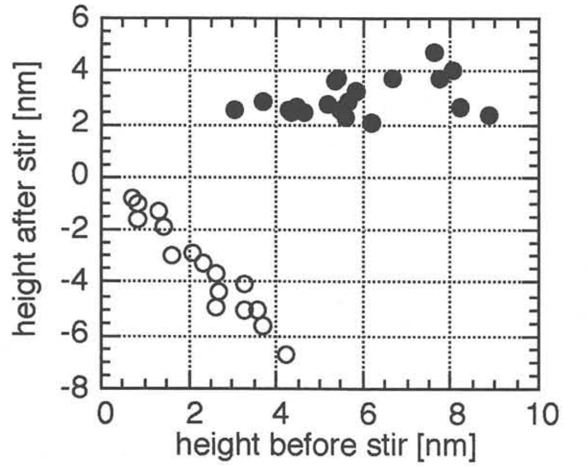


Fig. 3. Height of wire before/after stir in water for 10 minutes; closed circles show delta-doped HEMT; open circles show inverted-type delta-doped HEMT.

axis shows that the trench is formed. With the delta-doped HEMT the surface of which is undoped AlGaAs, the oxide wire remains after the stir in water. However, with the inverted-type delta-doped HEMT the surface of which is n-type GaAs, the trench was formed; moreover, the absolute value of the depth was approximately 1.5 times larger than the height before the stir. This result suggests that the latter is easier to design than the former, because we can calculate the local potential in the 2DEG channel for devices without the oxide wire.

The cross-sectional view of fabricated devices is shown in Fig. 4. The epitaxial layer consists of undoped GaAs (500 nm thick), undoped AlGaAs (100 nm), a delta-doped Si layer (3.3×10^{12} cm^{-2}), undoped AlGaAs (4 nm),

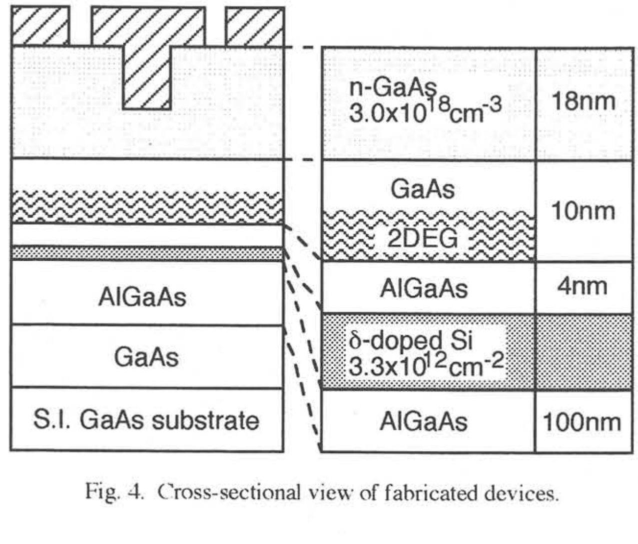


Fig. 4. Cross-sectional view of fabricated devices.

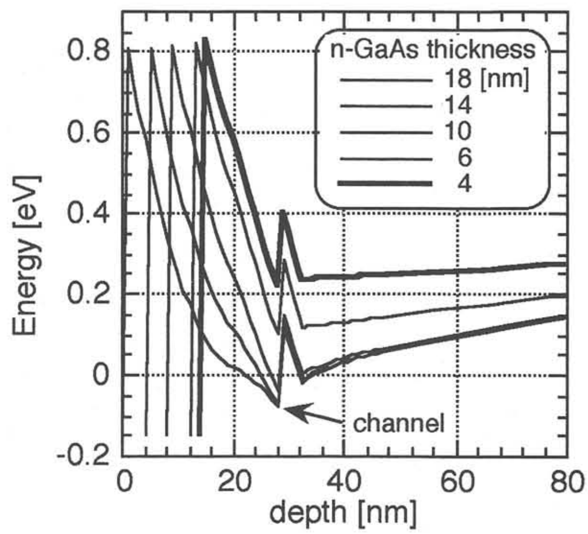


Fig. 5. Conduction-band diagrams.

undoped GaAs (10 nm), n-type GaAs (3.0×10^{18} cm^{-3}, 18 nm) on a semi-insulating GaAs substrate. Figure 5 shows the conduction-band diagram calculated at the gate voltage of 0 V using Poisson-equation. The potential of the channel increases as the thickness of the top layer decreases. If we fabricate the trench of 14 nm depth, we should obtain the potential barrier of 0.3 eV.

We observed the drain current for fabricated devices with trenches of various depths, as shown in Fig. 6. The y-axis is normalized by the current at 0 nm depth. The current decrease indicates that the height of the potential barrier has increased.

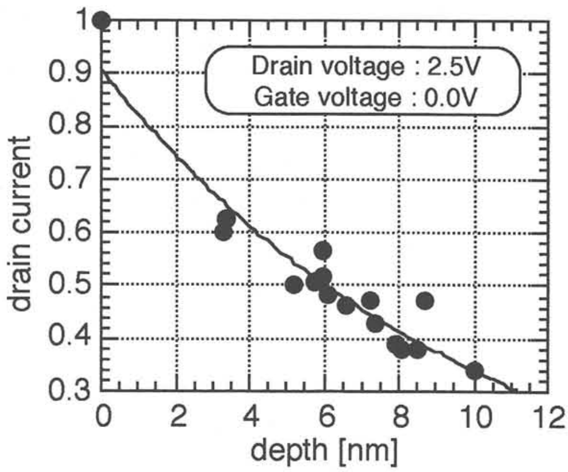


Fig. 6. Relation between drain current and depth of trench.

3. Conclusion

The oxide wire which is formed on the n-type GaAs surface using the AFM is dissolved in the water. We have applied this property to forming the narrow trench on the inverted-type delta-doped HEMT surface and to controlling the height of the potential barrier in the 2DEG channel.

This approach will enable us to fabricate GaAs/AlGaAs quantum effect devices and single-electron devices .

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