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Kelvin Probe Force Microscopy for Potential Distribution Measurement of Cleaved Surface of GaAs Devices

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Kelvin probe force microscopy (KFM) was successfully applied to the measurements of two-dimensional potential distribution of cleaved surface of GaAs devices under bias voltage. It was shown that the voltage resolution is less than 10 mV. The measured potential profile of the ungated HEMTs shows potential ridge which corresponds to the channel. Current crowding phenomena are also confirmed at the edge of the drain electrode.

1. INTRODUCTION

As the dimensions of semiconductor devices decrease, characterization of their electrical properties at microscopic scale becomes very important. One of the most important structural properties to be characterized is nanometer-scale potential profile. Recently Nonnenmachen et al.[1] have developed Kelvin probe force microscopy (KFM), which is based on vibrating-capacitor method (Kelvin method). They measured contact potential differences on metal surface[1] and Si pn structures.[2] Vatel et al. applied this technique to the potential distribution measurement of thin InGaAs resistor.[3] Two-dimensional dopant profiles of Si pn structure were also reported.[4,5] Although KFM was proved to be effective in electrical characterization of the devices, there are no reports on the measurement of cross-sectional potential profile of the GaAs devices under bias voltage. This information is very important to understand the device operation mechanism and to design high-performance device structure. In this paper, we demonstrate that the KFM is applicable to the characterization of the cleaved GaAs device under bias voltage. The cross-sectional potential image of the ungated HEMT was successfully obtained.

2. EXPERIMENTAL

The KFM equipment used in this work is commercially available one based on a noncontact-mode AFM.[6] Figure 1 shows a schematic diagram of KFM measurement system. The measurements were carried out in an air ambient at room temperature. A Au/Cr-coated Si cantilever with 30 nm tip radius and a spring constant of 1.5 N/m was used for the measurements. The cantilever was driven by piezoelectric bimorph transducer at frequency ω_r which is slightly above the resonant frequency of the cantilever. An additional alternating voltage $V_{ac}\sin(\omega t)$ and a DC bias voltage V_{off} were applied to the sample holder to measure the surface potential V_S of the sample. The holder was electrically connected to the source electrode. To determine the sample surface potential, the DC bias voltage V_{off} is adjusted so that the amplitude of the ω component of the electrostatic force becomes zero. The sample surface potential can then be determined as $-V_{off}$. The sample-tip distance is controlled using ω_r force component similarly to the noncontact AFM mode. Hence two-dimensional potential image and topographic map can be obtained simultaneously.

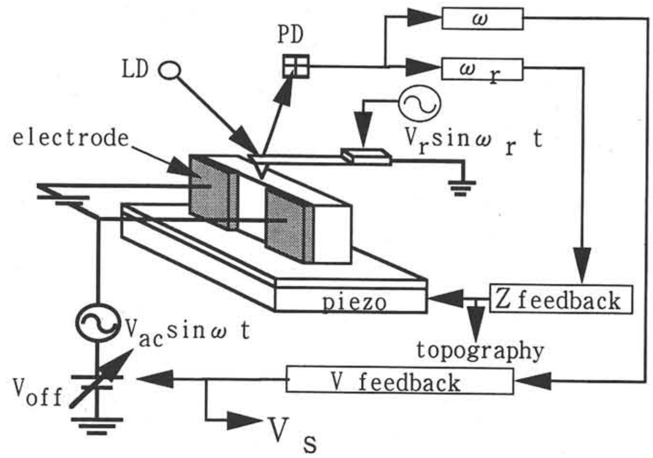


FIG.1 Schematic diagram of the KFM measurement system.

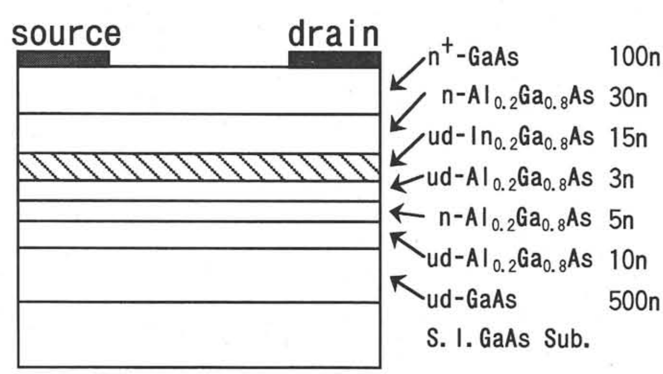
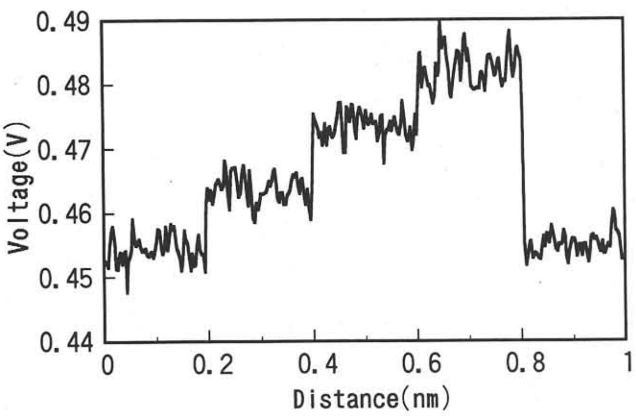


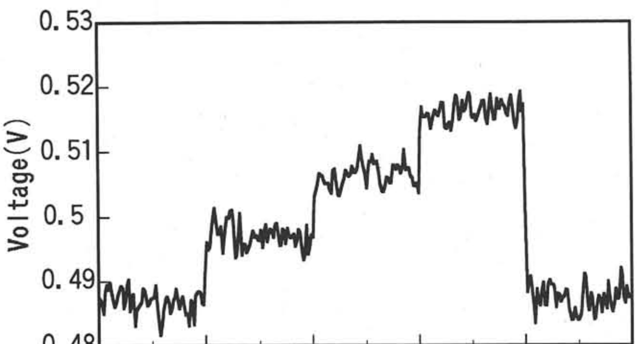
FIG.2 Schematic cross section of the measured device.

Figure 2 shows schematic cross section of the measured device. It was fabricated on an n-AlGaAs/ud-InGaAs/n-AlGaAs modulation-doped double heterostructure grown on a semi-insulating GaAs substrate by molecular beam epitaxy. After mesa isolation, source/drain ohmic contacts were formed by AuGe-Ni alloy. The distance between the electrodes is 4.5μm. After the cleavage, the device was mounted on a piezo-ceramic sample holder. The cleavage did not cause any detectable damage on the device I-V characteristics.

The voltage resolution was evaluated by changing the sample holder voltage stepwisely using external voltage source while the cantilever was being scanned on the constant-voltage area. Figure 3(a) is a result when the voltage step is 10 mV and the alternating voltage amplitude V_{ac} is 10 V. The 10 mV difference is clearly recognized even though some voltage fluctuation is observed, suggesting that the voltage resolution was less than 10 mV. When V_{ac} is increased to 20 V, the voltage fluctuation decreases as shown in Fig.3(b). Figure 4 is the dependence of the voltage fluctuation on V_{ac}. It decreases as V_{ac} increases and almost saturates when V_{ac} becomes larger than 10 V. The following experiments were consequently performed at V_{ac}=10 V.



(a)



(b)

FIG.3 Voltage change caused by applying changing the sample holder voltage stepwisely ; (a) V_{ac} = 10 V (b) V_{ac} = 20 V.

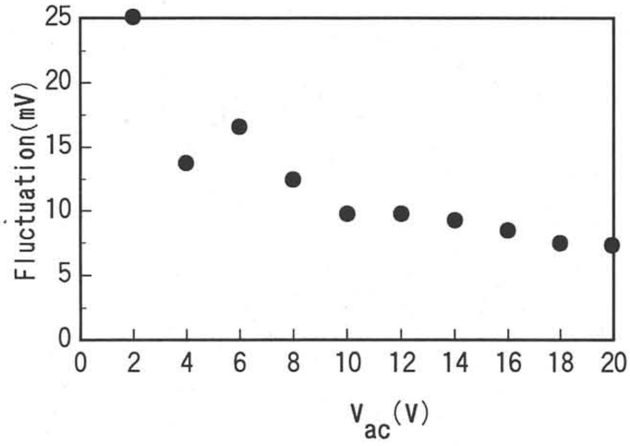
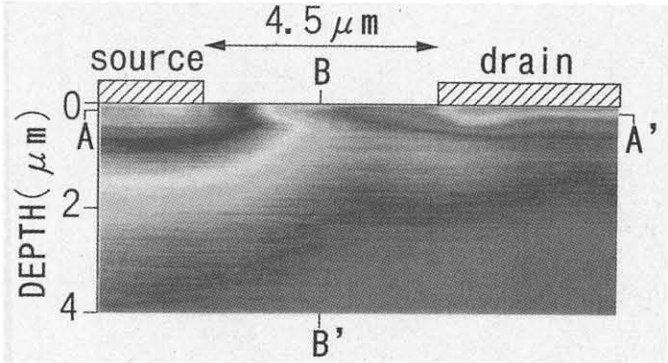
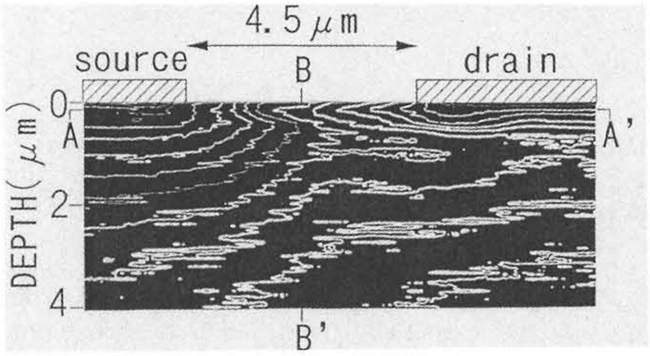


FIG.4 Dependence of voltage fluctuation on the alternating voltage amplitude.



(a)



(b)

FIG.5 (a) Measured two-dimensional image of the electrostatic potential. The bias voltage is 1.5 V. (b) Corresponding contour lines. The voltage step of each contour line is 40 mV.

Figure 5(a) and (b) show the measured two-dimensional image of the electrostatic potential and the corresponding contour lines when the bias voltage is 1.5 V. The voltage step of each contour line is 40 mV. We observed, from drain to source, a ridge of the contour lines at a position about 150 nm from the surface. The ridge is more clearly confirmed by the potential profile along the BB' line of Fig.5(b). The

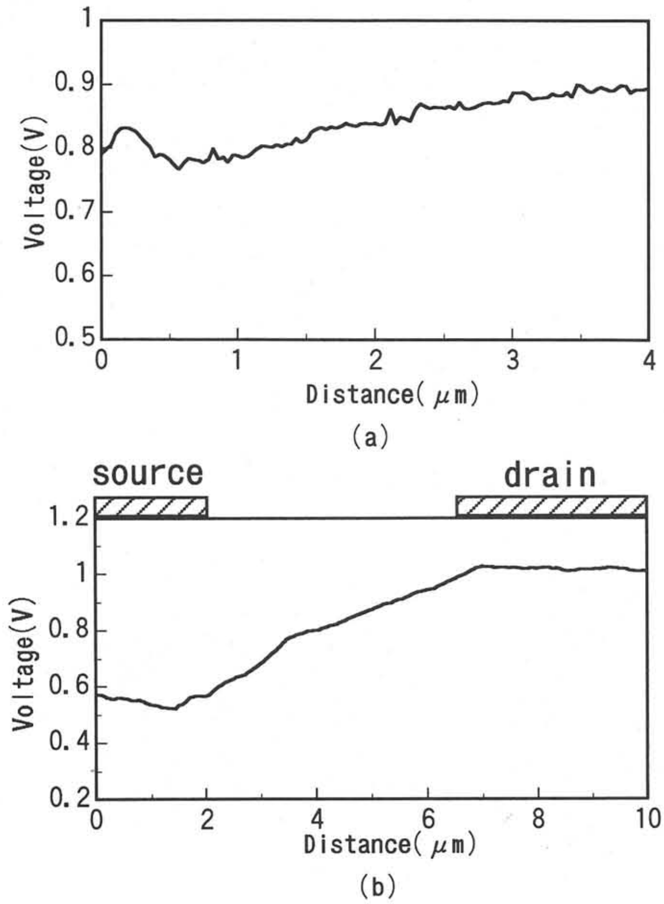


FIG.6 Potential distribution along the BB' line (a) and the AA' line (b) of Fig.5(b).

potential peak is observed near the surface as shown in Fig.6(a). The ridge reflects the electron path from source to drain, which is composed of 100 nm n^{+}-GaAs cap and InGaAs channel. The surface potential difference between the hetero-epitaxial layers could not be resolved. It is probably necessary to improve the spatial resolution. The potential distribution parallel to the surface along the ridge AA' line is shown in Fig.6(b).The electric field is almost constant as shown in the figure. The potential underneath the electrodes is almost flat. This is due to the low-resistive alloyed n^{+}-regions. The ridge starting at the edge of the drain electrode is thought to be due to the current crowding phenomena, taking the flat potential profile under the drain electrode into account.

3. SUMMARY

Kelvin prove force microscopy has been successfully applied to the measurement of two-dimensional potential profile of the cleaved surface of the ungated HEMTs under bias voltage. The voltage resolution was less than 10 mV. A clear two-dimensional potential image of the cleaved device was obtained. Potential ridge which corresponds to the channel is observed. By analyzing the potential contour lines, it is concluded that the current crowding phenomena occur at the edge of the drain electrode. By combining the KFM method with two-dimensional device simulation, it will become a powerful tool to analyze the electrical properties of the device and to design high-performance devices.

Acknowledgment

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