On The Mechanism of Scanning Probe Microscope Tip-Induced Nano-Oxidation Process of GaAs

Yoshitaka Okada [1], Shinji Amano, and Mitsuo Kawabe

Institute of Materials Science, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305, Japan

1) Correspondence; okada@mat.ims.tsukuba.ac.jp

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Abstract

Scanning probe microscope (SPM) tip-induced oxidation process of GaAs(100) substrates have been investigated. Firstly, the effects of SPM drawing parameters such as tip bias voltage and writing speed as well as ambient humidity on the oxide line height and width have been explored. The rate of reaction and its dependence on electric field strength have been examined to understand the basic mechanisms involved in the tip-induced oxidation of GaAs. The rate of oxidation has been found to decrease rapidly with oxide film growth, which is explained at the simplest level in terms of self-limiting influence of decreasing electric field strength. The oxide stopped growing for field strengths <1-2$\times 10^7$ Vcm^{-1}. In addition, it has been found that the oxidation kinetics does not follow the simple Cabrera and Mott model of field-induced oxidation.

I. Introduction

There is a rapidly growing interest in the possible use of scanning probe microscopes (SPM) as the tools for the fabrication of nm-scale electronic devices such as single electron transistors (SET). Dagata *et al.* used a scanning tunneling microscope (STM) in air to conduct tip-induced oxidation of local regions of H-passivated Si (111) surface for use as etch masks [1]. A STM was also used in UHV to form Si oxide lines as narrow as 1 nm wide [2]. On the other hand, atomic force microscope (AFM) has become an attractive option for performing similar work. Most recently, AFM tip-induced oxide lines have been used as etch masks to demonstrate a Si metal-oxide-semiconductor field-effect transistor (MOSFET) [3] and side-gated Si FET [4]. On thin Ti metal films, Matsumoto *et al.* have successfully fabricated room temperature operable SET with 15 nm features [5].

In order to optimally use the SPM tip-induced oxidation process for the fabrication of nm-scale electronic devices, it is necessary to understand the mechanisms and kinetics of the process so that we can reliably control the featured characteristics. Though the mechanisms of SPM tip-induced oxidation process have been studied by several authors in the case of Si [6 -11], it has been scarcely studied for GaAs [12,13] and other related compound semiconductors. With this in mind, we have investigated the rate of reaction for SPM tip-induced oxidation of GaAs(100) substrates and its dependence on electric field strength in order to clarify the basic mechanisms involved in the GaAs oxidation process.

II. Experimental

The SPM local oxidation was performed in air on freshly etched n^+-GaAs(100) substrates [12]. Using both Au-coated and doped Si conductive tips, we performed an investigation on the effects of tip bias and writing speed on oxide height and width. For this purpose, a computer script directed the SPM to draw pairs of 1μm-long lines; one left-to-right, and another right-to-left, at tip voltages ranging 4 to 12 V. Cross-sectional measurements of height and width and were taken at more than three different points on each oxide line. The full line-pattern was drawn for tip writing speeds ranging 0.01 to 3.0 μm/s.

III. Results and Discussion

Figure 1 shows the height of GaAs oxide lines plotted for varying writing speed, or tip velocity. An Au-coated Si tip was used and the relative humidity at the time of experiment was ~40%. The total GaAs oxide thickness was measured to be roughly 1.5 times the oxide height. In Fig. 1, it shows a rapid decrease of oxide height h with increasing writing speed v for each tip bias and from the straight line fits, a relationship h proportional to -log(v) is obtained. Furthermore, the bias dependence on oxidation rate is an indication that the electric field plays an important role in

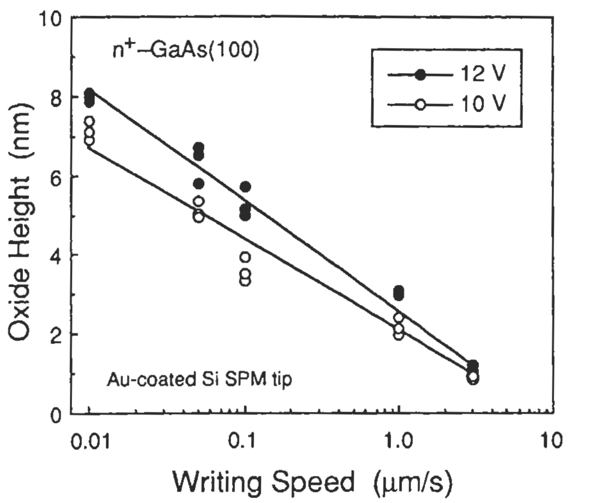

Fig. 1 The effects of SPM tip bias voltage and writing speed (tip velocity) on the height of oxide lines on GaAs(100) substrates. The relative humidity was ~ 40%.

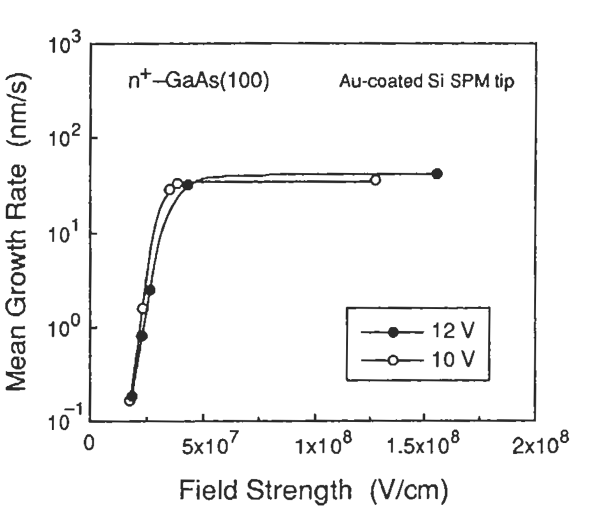

Fig. 2 The oxide growth rate plotted as a function of electric field strength. The GaAs oxide ceases to grow for electric fields <1-2 $\times 10^7$ Vcm^{-1}.

the AFM tip-induced oxidation process. The mean oxide growth rate was then calculated to the first-order approximation and plotted as a function of electric field strength as shown in Fig.2. Here it was assumed that the entire potential drops across the oxide, and the time which the tip interacts with a given location on the surface is given by the oxide linewidth divided by v. It can be seen that high initial oxidation rates (~50nm/s at 10 Vbias) decrease rapidly with decreasing electric field strength E, and the oxide practically ceases to grow for $E <\sim 2 \times 10^7$ Vcm^{-1}.

The general characteristics obtained here in the oxidation of GaAs are very similar to those reported for Si [6 -11], and thus it is expected that the underlying basic mechanisms of the SPM tip-induced oxidation process are generally identical in GaAs and Si. By applying a negative bias to a conductive SPM tip, an intense and localized electric field is created at the substrate close to the tip. There are two reported mechanisms; anodization through a thin film of water adsorbed to the substrate surface [6], and field-induced process that helps the ionized water species diffuse through the existing oxide. Such an oxidation process is often modeled by the Cabrera and Mott kinetics of field-induced oxidation [14].

However, the simple Cabrera and Mott model is applicable only to the oxidation of very thin oxide films and should give an analytical relationship of $1/h \propto \log(v)$ [10]. Thus this model alone cannot account for the observed $h \propto \log(v)$ kinetics as in this case, nor many of the results reported for SPM tip-induced oxidation of Si. Furthermore, it can be seen from Fig. 2 that the mean rate of oxidation is not only a function of electric field strength E, but also depends on the applied bias V itself, especially for high E. This also indicates that the observed kinetics do not obey the simple Cabrera and Mott model. Deviations from Cabrera and Mott type kinetics in the case of Si have been well investigated by Avouris *et al.* [11], where a large stress which builds up during the oxidation due to large volume

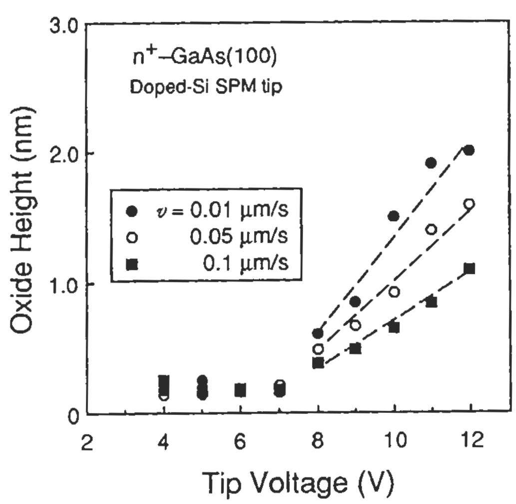

Fig. 3 Variation of the GaAs oxide height with the tip bias voltage measured for varying writing speed. The relative humidity was kept < 30% in this case.

mismatch between Si and SiO_2 and hence increases the activation energy for oxidation can partially account for these results. We believe similar effects take place in the case of GaAs.

Furthermore, whether the tip-induced oxidation is assisted by an anodization process can be studied by investigating the variation of h with tip bias V. The obtained results are displayed in Fig.3 with v chosen as a parameter. This was a separate experiment as from Fig. 1 and a doped Si tip was used. The relative humidity at the time of experiment was kept below ~30%. The vertical resolution was ~ 0.2nm, which was limited by the average roughness of substrate. It can be observed that for a given v, h increases almost linearly with V, which is a general characteristic of anodization process. To further note, it did not result in measurable oxidation for $V < \sim 7$ V. This implies that there is a minimum threshold voltage for the oxidation to take place [8,9]. A threshold voltage also existed even when an Au-coated Si tip was used instead.

IV. Summary

We have investigated the rate of reaction for the SPM tip-induced oxidation of n^+-GaAs (100) substrates and its dependence on electric field strength. The basic mechanisms involved in the oxidation of GaAs have been studied. The rate of oxidation was found to decrease rapidly with oxide film growth which was explained at the simplest level in terms of self-limiting influence of decreasing electric field strength. The oxide stopped growing for electric field strengths $< \sim 2\times10^7$ Vcm^{-1}. Other important mechanisms and kinetics were also discussed in comparison with the results reported for tip-induced oxidation/anodization of Si. However, it should be noted that the exact microscopic mechanisms remain speculative at present because both the chemical and the physical natures of GaAs oxide produced by this technique are not well understood. Finally, the authors would like to acknowledge Prof. J. S. Harris and B. Shimbo of Stanford University for their stimulating discussions and support.

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