# Current-dependent silicon oxide growth during scanned probe lithography

T.G. Ruskell, J.L. Pyle, R.K. Workman, X. Yao and D. Sarid

*Indexing terms: Lithography, Atomic force microscopy*

Measurement of picoAmp currents during silicon oxide growth by scanning probe lithography is reported. The observed current is attributed to the reduction of $H^+$ ions produced by the oxidation process. The local electrical quality of the nanofabricated oxide lines, probed by local Fowler-Nordheim tunnelling, is found to be uniform and highly insulating.

*Introduction:* Interest has grown in the field of nanolithography since Dagata *et al.* reported on the local growth of silicon oxide on hydrogen-terminated silicon surfaces stimulated by scanning tunnelling microscopy [1]. Recently, conducting tip atomic force microscopy (AFM) has become the method of choice for the generation of local field-induced silicon oxide patterns. In this method, nanometre scale patterns are grown as a negatively-biased AFM tip scans across the sample. Much research has focused on developing high quality tips for the nanolithography process, and extending this technique to other materials and nanometre scale device fabrication [2, 3].

It has been proposed that the highly localised electric fields surrounding the AFM tip play a key role in the oxidation of HF treated silicon surfaces in the presence of water [1, 4]. However, previous measurements limited by a sensitivity of 10pA have shown no clear evidence of current flow during AFM nanolithography [5]. We present evidence that nanolithography is governed by a current flow which determines the amount of oxide growth. It is suggested that this current results from the reduction of $H^+$ ions produced by the oxidation process. Quantitative analysis of the current flow during nanolithography will make it possible to design a system that regulates oxide growth in a highly controlled manner.

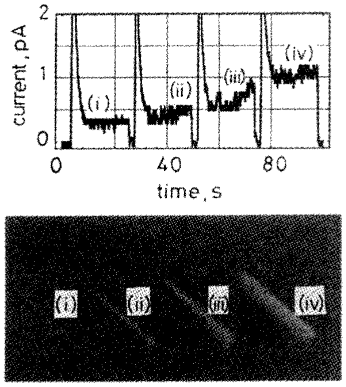

**Fig. 1** *Measured current while writing four lines with a silicon tip and resulting lines of silicon oxide*

Image size: 5 × 2.5µm², black to white contrast: 5nm

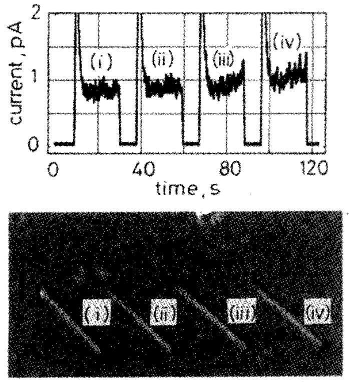

**Fig. 2** *Measured current while writing four lines with Cr-coated $Si_3N_4$tip and resulting lines of silicon oxide*

Image size: 5 × 2.5µm²; black to white contrast: 5nm

*Experiment:* The principles of a conducting probe AFM system with a current sensitivity of ≃ 100fA operating in air, used for Fowler-Nordheim voltage mapping of oxide layers, has been described elsewhere [6]. For the nanolithography experiments described here we use commercially available *n*-type Si- and Cr-coated $Si_3N_4$ cantilevers [7]. The substrates used were 100Ω cm, *n*-type Si(100), etched in a standard buffered HF rinse to produce oxide-free H-terminated Si(100) surfaces. Each tip, biased at –12V with respect to the sample, was used to write at a speed of 0.06µm/s. Measurements of the current were made while writing four adjacent diagonal lines from the top left to the bottom right of the sample.

Fig. 1 shows the measured current against time while writing with the Si tip, together with the resulting lithography. Displacement current spikes are seen at the beginning of each line upon the application of the voltage. At the end of each line, the voltage was turned off, and the tip moved to the beginning of the next line, during which time no current flow was observed. There is a clear correlation between the steady state current flow and the height and thickness of each written line. Fig. 2 shows similar measurements obtained with the Cr-coated $Si_3N_4$ tips. The consistent current flow results in very uniform lines.

Approximately 60 × 10⁶ atoms of oxygen are required to produce the volume of $SiO_2$ in line (iv) of Fig. 1. The integrated charge while writing that line was ≃ 150 × 10⁶ *q*. To incorporate an oxygen atom into the surface lattice from the native water layer requires the release of two $H^+$ ions [4], which are reduced at the tip, resulting in the measured current flow and the formation of $H_2$. We thus obtain excellent agreement between the measured charge and the calculated charge of 120 × 10⁶ *q* required to produce the observed amount of $SiO_2$.

To further characterise the nature of the lithographed lines, a voltage map [6] of the area in Fig. 2 was made. A rectangular platinum/iridium wire with a cross-section of 100 × 50µm², bent at the end and electrochemically etched to form a tip, was used as a conducting AFM cantilever. Topography and voltage maps were obtained simultaneously, the latter using a second feedback system to maintain a constant tip-sample current of 10pA. The resulting images shown in Fig. 3 demonstrate the quality of the grown oxide measured by the relatively large tip sample bias of –32.5V required on the $SiO_2$ regions.

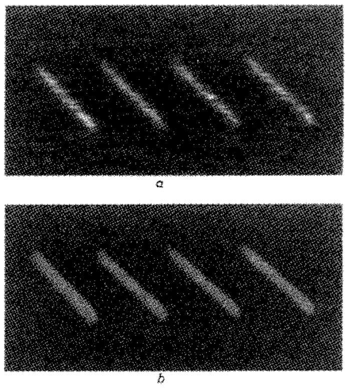

**Fig. 3** *Measured current and voltage map*

*a* The same lines as shown in Fig. 2 imaged with a Pt/Ir tip, black to white contrast: 5nm
*b* Resulting Fowler-Nordheim voltage map, black to white contrast: 0 to –32.5V, image size: 5 × 2.5µm²

*Summary:* Accurate current measurements during nanolithography have been performed for the first time and attributed to the reduction of $H^+$ ions at the tip. The results reported here will make it possible to improve the control of oxide growth using conducting tip AFM nanolithography.

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# Determination of the temporal plasma density above a semiconductor bridge

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*Indexing terms: Plasma, Semiconductor bridges*

A new method of determining the temporal plasma density above a semiconductor bridge using a microwave resonator probe has been proposed. Experimental results indicate that the plasma density is observed to increase to a peak value of $4.2 \times 10^{11}\,\text{cm}^{-3}$ and decay exponentially with time, which is consistent with diffusion dominating the plasma transport.

*Introduction:* A semiconductor bridge (SCB) is a small electronic device designed to replace a hot wire in setting off explosives [1, 2]. It is driven by a short (~µs), low energy pulse (~mJ) that melts and vapourises the silicon bridge when a very high current density ($\geq 10^6\,\text{A/cm}^2$) flows through it, creating a hot plasma that can ignite explosives. Since the SCB is a plasma generator for the ignition of explosives, information on plasma constituents, identification of emitting species [1, 3], plasma temperature [3], and plasma density is critical to attain a better understanding of the SCB discharge behaviour. The measurement method of the temporal plasma density distribution above the SCB device has not been published in the literature of plasma density properties of SCB devices. The purpose of this Letter is to report a determination method of the temporal plasma density above the SCB device at a given distance between the probe and the surface of the bridge in vacuum.

*Measurement method and experimental results:* In this study, we use a microwave resonator probe to determine temporal plasma densities above the SCB device. The technique used here is based on measuring the cold plasma permittivity, and is largely independent of sheath and thermal effect. Unlike the more familiar cavity resonance shift method, it is suited for localised plasma density measurements. In a plasma with a dielectric constant given as $\varepsilon_p = 1-\omega_p^2/\omega^2$, the resonance frequency of a quarter-wavelength of transmission line $\omega_{res}$ is increased from its value in vacuum $\omega_{ores}$ to

$$\omega_{res}^2 = \omega_{ores}^2 + \omega_p^2 \qquad (1)$$

Therefore, a measurement of the probe resonance frequencies in vacuum and in a plasma allows the plasma frequency or density through

$$n_e = \frac{\omega_p^2 \varepsilon_0 m_e}{e^2} \qquad (2)$$

where $\varepsilon_0$ is the permittivity of free space, $n_e$ is the plasma electron density, and $m_e$ and $e$ are the electron mass and charge, respectively, to be obtained quickly.

The probe, described in detail elsewhere [2], consists of a quarter-wavelength parallel transmission line section with one open and one shorted end acting as a resonant structure. The probe was formed from pure silver wire with a diameter of 0.05mm. A pair of magnetic loops are used for exciting the resonator and detecting the signal. The observed vacuum resonance of the probe used is ~5.5GHz.

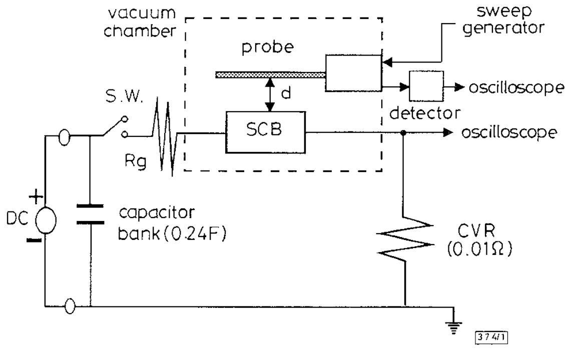

**Fig. 1** *Experimental setup for measurement of plasma electron density using microwave resonator probe*

A block diagram for the microwave resonator probe measurements is presented in Fig. 1. The probe was located 1cm above the bridge. The microwave resonator probe was excited using a sweep oscillator. The output of the resonant probe was fed into a crystal detector with frequency responses of 0.01–18GHz. The oscilloscope is only triggered when the SCB generates a plasma. The probe response was finally displayed on a fast oscilloscope. The firing set used in these experiments is a capacitor discharge firing set. A capacitor bank (0.24F) was used to produce a constant voltage pulse, and a current viewing resistor (CVR) was used to measure voltage across the resistor in order to calculate the current flowing through it. The bridges were fired in vacuum using a capacitor of 0.24F capacity charged to 5.5V.

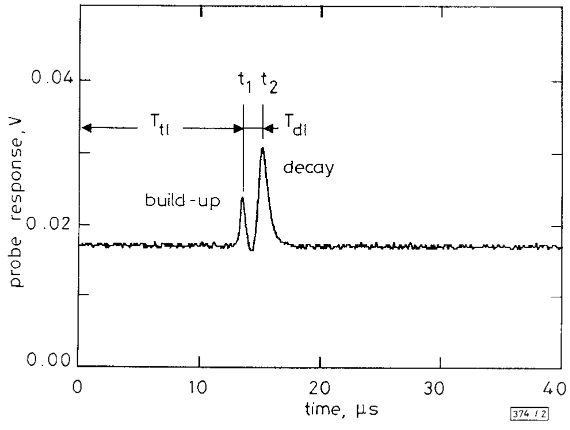

**Fig. 2** *Oscillography of output of microwave resonator probe excited at a single frequency and responding to a building-up and a decaying plasma*

The plasma produced by the SCB device is time-varying. The presence of plasma expanding from the SCB causes a shill in the resonance frequency of the probe. To measure the temporal evolution of the plasma electron density, a number of shots were taken under the same firing conditions and different microwave frequencies at a given distance $d = 1\,\text{cm}$. The method of determining the