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The Scanning Capacitance Microscope as a Characterization Tool for Semiconductor Devices

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1.Introduction

Three variations of scanning capacitance microsocpy (SCM) have been demonstrated based on either a video disc system,[1] scanning tunneling microscopy (STM)[2] or atomic force microscopy (AFM).[3] Since the capacitance between the probe and the sample is too small to measure its absolute value, its change is usually measured. In the case of video disc system-based type SCM, the difference of the capacitance at different locations is measured. With STM- or AFM-based SCM, modulation methods are used to induce a capacitance change. In STM-based system, the tip-sample distance is modulated by a piezo actuator, which modulates the corresponding capacitance. In AFM-based SCM, modulation is induced by applying an ac voltage between the probe and the sample. Among these three types of SCM, contact type AFM can be considered superior, since it can simultaniously measure both the surface topography of a sample and the capacitance between the SCM probe and the sample while keeping complete independence between the two signals. Contact type AFM achieves higher sensitivity due to there beeing no space between the probe and the sample surface.

2. Principle

Figure 1 shows a schematic diagram of a SCM combined with a contact mode AFM including an optical lever. The capacitance sensor used is a Videodisc capacitive pick-up circuit developed for a VHD video system (JVC) and is similar to RCA's.[4] It can measure tip-sample capacitance with a sensitivity of 10^{-19} F. The capacitance sensor consists of an oscillator, an LC resonator and a detection circuit. A microwave signal (about 1 GHz) from the oscillator is coupled through the resonator to the detection circuit. A change in the tip-sample capacitance shifts the resonant frequency of the resonator, thus changing the output signal. An ac modulation voltage and a variable dc bias voltage are applied to the sample which is placed upon a piezo-tube scanner. The ac component of the output signal (dC/dV) is detected using a lock-in amplifier.

The metal tip and the silicon sample with its oxide layer form a very small metal-oxide-silicon (MOS) structure, as shown in Fig. 2 (a). If a positive bias voltage is applied to the n-type silicon sample against the tip, the tip-sample capacitance decreases due to the depletion layer generated in the silicon under the tip.[5] In the case of p-type silicon, capacitance decreases when a negative bias is applied to the silicon.

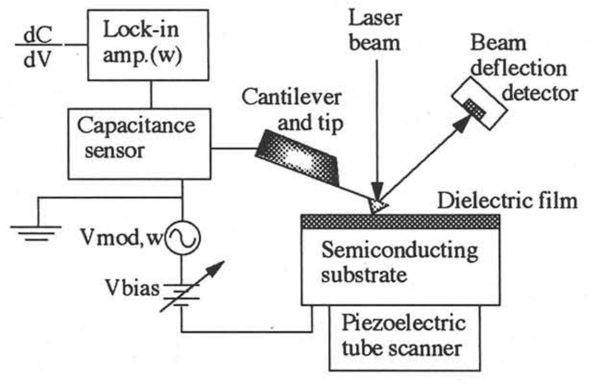

Fig. 1. Schematic diagram of our SCM/AFM.

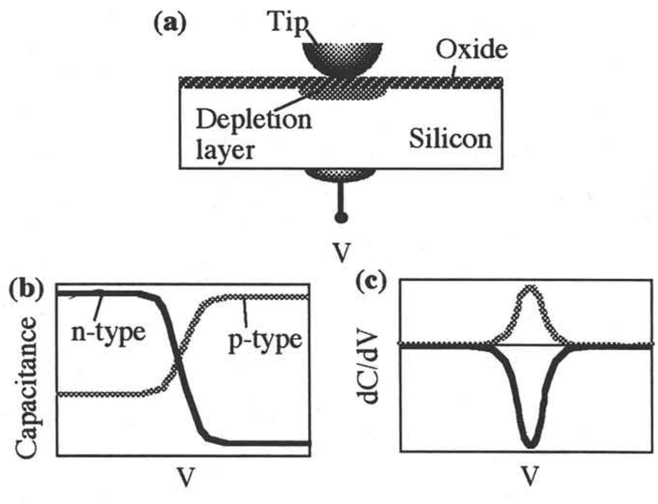

Fig. 2. (a) Configuration of the tip and the silicon sample with its oxide layer. The tip and the sample form a MOS structure. (b) Calculated C-V curves for n-type and p-type silicon, when bias voltages (V) are applied to the silicon. (c) dC/dV-V curves derived from the C-V curves.

The amount of the capacitance change depends on the dopant density. If the dopant density is high, the capacitance change is small, since the depletion layer created by the bias voltage is thin. High frequency capacitance-voltage (C-V) characteristics are shown in Fig. 2 (b), in which the dopant density of p-type silicon is assumed to be higher than that of n-type. Figure 2(c) is derived from the curves in Fig. 2(b). Since the dC/dV-V curves in Fig. 2(c) show a positive peak for p-type silicon and a negative peak for n-type, it is possible to determine the dopant type from SCM measurement.

3. Application to Semiconductor Device Characterization

Various types of samples used in reported applications of SCM including our own are shown in Fig. 3. The sample shown in Fig.3(a) involved the study of dopant regions or concentrations both from the wafer surface and from its cross section. As we have demonstrated, SCM can be useful for dopant failure analysis.[6,7] Dopant profiling of a cross section is another hopeful application currently under investigation by several groups.[8-11]

The second sample shown in Fig.3(b) was used in the characterization of a dielectric thin layer as silicon oxide.[12] This application implies that we can characterize thin insulator layers with better than 50 nm lateral resolution. Not only thickness differences, but also breakdown fields can be studied.

Researchers are currently trying to use ferroelectric materials in semiconductor devices. SCM has been applied to the characterization of a sample comprised of a ferroelectric thin layer deposited on a metal substrate, as shown in Fig.3(c).[7]

Using the sample shown in Fig.3(d), we demonstrated that SCM was able to detect buried metal lines or gates in semiconductor devices.[13]

Application of SCM to memory were demonstrated using the NOS system[3,14,15] shown in Fig. 3(e) and by using a ferroelectric/semiconductor system.[16] These are not exactly applications to semiconductor devices, but such memory systems depend on semiconductor characteristics.

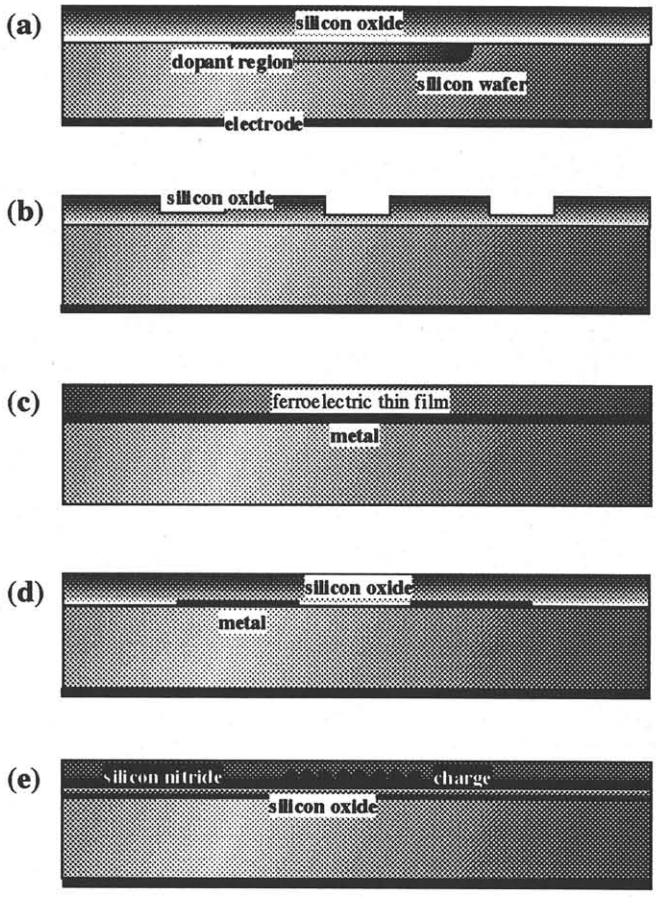

Fig.3 Various samples for SCM application.

4. Conclusion

Among the several kinds of scanning capacitance microscope (SCM) developed, contact-type AFM-based SCM has the advantage of having no cross talk between the topographic and capacitance signals. Furthermore, Contact type AFM achieves higher sensitivity due to there beeing no space between the probe and the sample surface. We believe that contact-type AFM-based SCM is promising as a characterization tool for semiconductor devices.

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