

Inspecting wafers using a potential difference imaging sensor method

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Contamination and chemical residue are two major causes of reduced yield in semiconductor fabrication. Wafer cleanliness is becoming increasingly important as minimum feature sizes shrink below 90 nm, where the thickness of adsorbed layers and organic contaminants are of the same order as the process tolerances of functional films in devices. Contamination, whether organic or metallic, can cause process variation and defects, such as poor coverage, vacancies, voids, leakage, shorts, and overburdens. For example, a small amount of metal contamination in the bulk semiconductor substrate can cause the bulk minority carrier lifetime to decrease because the metal contamination may assist in the recombination of electrons and holes in the semiconductor substrate. That effect would have a detrimental impact on the DRAM refresh rate. To increase yields in semiconductor wafer fabs, it is crucial to reduce contamination and minimize residues.

Contamination and residues can be detected using optical or analytical metrology tools. Although optical inspection systems are often fast enough to perform in-line inspection of production wafers, they are not well suited for detecting film nonuniformities or small amounts of contamination that are not optically visible. Total x-ray fluorescence (TXRF) or time-of-flight secondary ion mass spectroscopy analysis tools provide a wealth of information on wafer surface chemistry, but they are expensive, slow, or destructive and do not provide information on the entire wafer surface.

Detecting and controlling contamination effectively during wafer processing requires a fast, in-line, nondestructive method of detecting minute chemical changes on the wafer surface. This capability would lead to cost savings by minimizing the time required to detect contamination, thereby reducing the number of wafers affected and the associated costs of scrap or reduced device reliability. This article describes a new sensor technology and system developed by Qcept Technologies (Atlanta) for imaging and detecting chemical contamination on IC wafers. The system operates by detecting variations in work function across the surface of the wafer.

Vibrating Kelvin Probe versus Nonvibrating CPD Probe

Vibrating Kelvin Probe. The work function of an electronic conductor is defined as the minimum amount of work required to move an electron from the Fermi level of the bulk material to the vacuum level. In other words, it is the energy required to move an electron from the interior of the conductor to a noninteracting point outside the surface (beyond the image charge region).

Because work function is a fundamental property of a material surface, it is of interest in a wide range of surface phenomena. The work function of a particular material varies if contaminants or coatings are present. Such variations can be analyzed to determine the cleanliness of a surface, the uniformity or thickness of a coating, and other information

about the condition of the material surface. Work-function measurement can be used to study semiconductor doping, organic semiconductors, organic monolayers, surface reactivity, biological systems, heterogeneous catalysis, and corrosion.

The work function of a surface is typically measured using a vibrating Kelvin probe. This probe operates by measuring contact potential difference (CPD), which is the electric potential that forms between two materials with different work functions when they are electrically connected. CPD is proportional to the work-function difference between two surfaces.

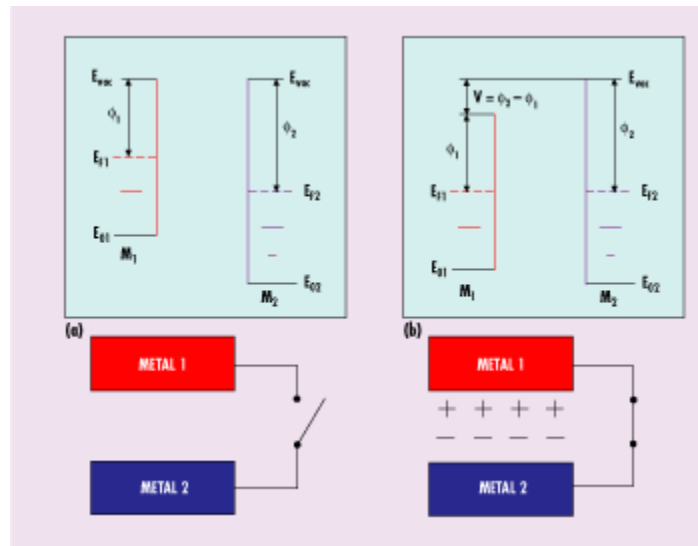


Figure 1: Schematic diagrams showing the energy and contact potential difference of two metals (a) before and (b) after contact.

The concept of CPD is illustrated in the schematic diagrams shown in Figure 1. In Figure 1a, two different metals, with different work functions and Fermi levels, are placed in close proximity to each other but are not connected. The figure shows the electron energy levels along with the work functions Φ_1 and Φ_2 . If the two metals are then electrically connected, as shown in Figure 1b, electrons flow from the material with the smaller work function (Φ_1) to the material with the larger work function (Φ_2), resulting in an accumulation of charge on the two metals and the formation of an electric field between them. The amount of charge that is formed is equal to the product of the capacitance between the two metals and their CPD.

The vibrating Kelvin probe operates by measuring the CPD between a probe of known work function and a surface of unknown work function. The probe is vibrated over the surface to be measured. This vibration causes a periodic variation in capacitance between the two materials, which results in a time-varying current into the probe. This current is measured and nullified by applying an opposing voltage on the probe or surface. This voltage, known as the backing potential, results in zero current when it is equal to the CPD between the two materials.

Vibrating Kelvin probes have been used in a wide variety of applications, including the measurement of dielectric layer thickness and contamination inside the dielectric layer.^{1,2} While they can be used to form images of work-function variation across surfaces, the need to vibrate the probe and adjust the backing potential results in limited data acquisition rates that are not compatible with fast-cycle-time, high-resolution imaging applications.

Nonvibrating CPD Probe. The nonvibrating contact potential difference (nvCPD) measurement technique is a variant of the traditional vibrating Kelvin probe method. Instead of vibrating the probe, the nvCPD sensor detects work-function variations by translating the probe relative to the sample surface. Variations in work function across the surface result in variations in CPD and the associated voltage between the probe and the surface. These voltage variations produce a small current into the probe that can be amplified and sampled. The use of translation instead of vibration results in a dramatic improvement in the data acquisition rate.

While vibrating Kelvin probes typically acquire data at several samples per second, the nvCPD probe can acquire data at millions of samples per second, making it suitable for high-speed imaging applications. In fact, the faster relative motion between the nvCPD probe and the surface of the wafer results in an increase in signal strength (within the bandwidth limits of the amplifier). The sensor's increased scanning speed makes it useful as an in-line tool for contamination detection.

In both the vibrating and nonvibrating CPD sensors, the sensor probe and the measured surface form a capacitor. The well-known formula for the charge on a capacitor is simply

$$Q = CV$$

where Q is charge, C is capacitance, and V is voltage. The current i into a capacitor is obtained by differentiating the first equation:

$$i = \frac{dQ}{dt} = C \frac{dV}{dt} + V \frac{dC}{dt}$$

For both vibrating and nonvibrating sensors, the voltage across the capacitor is the CPD resulting from the difference in work function between the probe and surface. The vibrating probe determines the CPD by applying a backing voltage (V_b) to zero the current during vibration ($i = 0$ when $V_b = -V_{cpd}$). The resulting backing voltage is equal in magnitude, and opposite in sign, to the CPD:

$$i = (V_{cpd} + V_b) \frac{dC}{dt}$$

In contrast, the nonvibrating probe detects changes in voltage across the capacitor while the probe moves relative to the surface. If the surface is relatively smooth and the gap between the probe and surface is relatively constant, the capacitance is constant. The resulting current into the probe is given by:

$$i = C \frac{dV_{cpd}}{dt} = C \frac{dV_{cpd}}{dx} \frac{dx}{dt} = Cv \frac{dV_{cpd}}{dx}$$

where v is the relative velocity of the probe and underlying surface, and dx represents the change in relative position. Any variation in CPD generates a current into the probe. Since the work function of the probe is fixed, the probe signal is proportional to the work-function variation across the surface.

Mapping Work-Function Variation

Qcept Technologies has developed the Chemetriq wafer-scanning system for mapping the work-function variation on silicon wafers. Based on a patented nonvibrating nvCPD sensor and proprietary imaging software, the system produces information that can be used to assess chemical variation across wafer surfaces.

Pictured in Figure 2, the system measures the electric potential difference between the sensor probe tip and the silicon wafer surface, quickly generating whole-wafer images of work-function variation. Sensitive to minute traces of contaminants and residues, the sensor detects surface chemical and geometric nonuniformities that cannot be detected easily using other metrology tools. Contamination on the wafer surface, including bulk contamination and submonolayer surface residues, can be mapped.

Scanning time, which depends on the required resolution, can vary from less than one minute to several minutes for entire 200- or 300-mm wafers. The sensor and system are well suited for performing nondestructive, real-time contamination inspection and characterization. The stand-alone inspection tool can be integrated as an in-line metrology tool in the fab for performing in situ monitoring, providing a go/no-go assessment of wafer cleanliness.



Figure 2: The core module of the nvCPD wafer-scanning system.

The wafer-scanning system includes a spindle and a three-axis linear motion system. The nvCPD sensor and the scan- height sensor are mounted on the linear motion stages. The wafer is mounted on a vacuum chuck attached to the spindle. When the wafer is spun, a sensor measures the wafer height and adjusts the gap between the nvCPD sensor probe tip and the wafer surface. After the linear motion system positions the nvCPD sensor above the wafer surface, concentric, circular tracks of data are acquired as the sensor scans the wafer from the outer edge to the center. Data are collected, stored in a computer, and then processed with software to generate images and quantitative data on wafer nonuniformity.

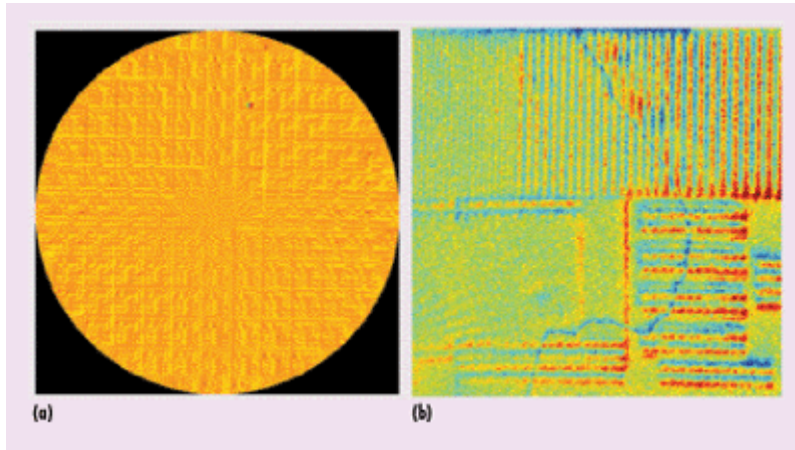


Figure 3: Work-function image of (a) a full 200-mm postcopper CMP process wafer with a Sematech 831AZ pattern, and (b) an enlarged section of the same wafer showing the work-function variation on the copper/dielectric surface inside a die after CMP processing.

Figure 3a shows a typical full-wafer nvCPD scan of a 200-mm copper wafer that has undergone a two-step CMP process. The image contains more than 10 million data points and can be manipulated to examine an enlarged area of interest. Figure 3b shows a sample area of interest consisting of a single die.

Experiment Results

Two experiments were conducted to test the sensitivity of the nvCPD sensor at detecting contamination on silicon wafers. Two types of wafers were prepared. In the first experiment, different types of thin metal films were deposited on the same silicon-substrate wafer to compare the nvCPD signal with the work function of the metal materials. In the second experiment, a wafer with copper contamination was tested. Both wafers were scanned using the sensor/software system.

Correlation between CPD and Work Function. In this experiment, the wafer was divided into quadrants, and each quadrant underwent unique deposition processing. Using dc sputtering, four different materials were deposited onto different quadrants of a silicon substrate through a shadow mask. The first quadrant was sputtered with copper, the second with chromium, the third with titanium, and the fourth with aluminum. Sputtering time was set to achieve a film thickness of 100 Å in all quadrants.

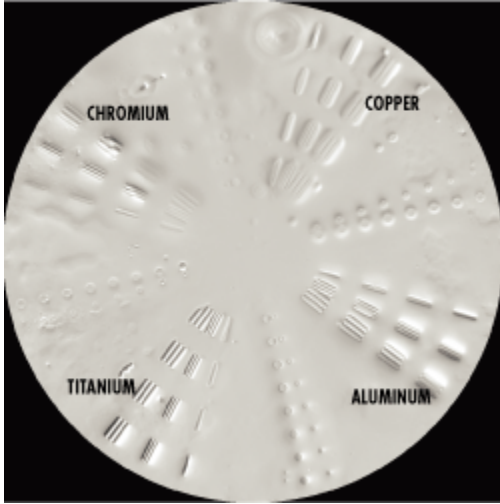


Figure 4: Wafer images of four different metal thin films taken using the nvCPD system.

highest.

CPD signal intensity can be compared with the work function of materials. Table I lists the electronic work function Φ of the silicon substrate and the four metals deposited on the wafer surface. The work-function difference ($\Delta\Phi$) between the deposited film and the silicon substrate is also calculated. The table indicates that there is a good correlation between the CPD signal intensity (V_{cpd}) and $\Delta\Phi$. The higher the work-function difference, the higher the CPD signal intensity. This correlation is shown in Figure 6, where the CPD signal intensity increases linearly with the work-function difference between the deposited film and silicon substrate.

A CPD image of the wafer is shown in Figure 4. The lines and dots indicate the areas where metal films were deposited. In all four quadrants, features were detected by the nvCPD sensor with different intensities and contrasts. The CPD signal intensity was the voltage change measured by the probe as it passed from over a silicon substrate region to a deposited-metal region. Signal intensity can be extracted from either a trackwise line plot or straight line plot. In this case, trackwise line data were used for characterization. Figure 5 shows that the peak-to-peak intensity of the CPD signal varied with the four metals. The copper film generated the lowest peak intensity and the titanium the

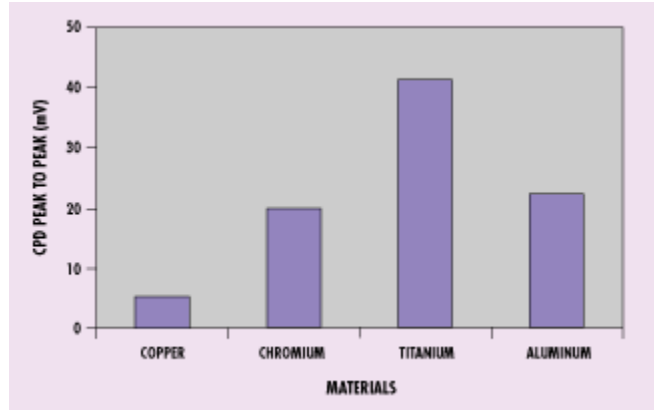


Figure 5: CPD peak-to-peak intensity versus four metals.

Material	Φ (eV)	$\Delta\Phi$ (eV)	V_{cpd} (mV)
Silicon	4.85	—	—
Copper	4.65	0.2	7.31
Chromium	4.5	0.35	25.92

Titanium	3.7	1.15	52.91
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Table I: Work function (Φ) and work-function difference ($\Delta\Phi$), which is determined by $\Phi_{\text{Film}} - \Phi_{\text{Si}}$.

Copper Contamination. In the second experiment, the sensitivity of the nvCPD sensor to copper residue was tested. The copper contamination was intentionally introduced onto a silicon wafer with a solution containing copper sulfate pentahydrate. First, the solid Cu (II) sulfate pentahydrate was diluted in methanol to different concentrations ranging from 10^{-2} mol/L to 10^{-7} mol/L. Then a drop of each solution about 12 mm in diameter was dispensed onto a specific location on the wafer surface. A total of six spots were deposited on the wafer at a radius of 30 mm. The wafer was allowed to dry through evaporation and then measured using the wafer-scanning system.

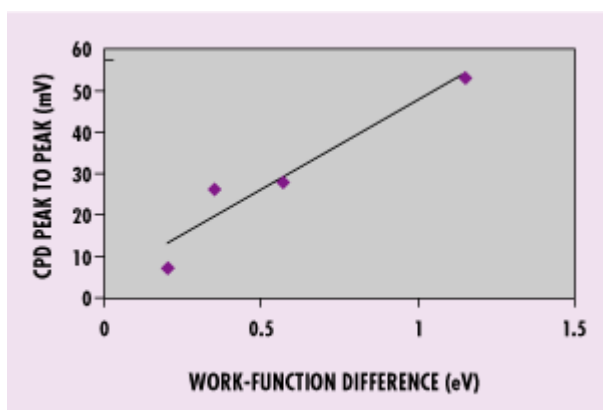


Figure 6: CPD signal intensity versus the work-function difference.³

using the nvCPD technique.

Figure 8 demonstrates the correlation between the work-function variation and copper surface concentration as measured by TXRF. It can be seen that the signal intensity increases gradually with the increasing copper concentration but then levels off at still higher concentrations. This phenomenon is in agreement with the theoretical prediction. Work function is an inherently surface phenomenon. Once a surface layer is contiguous and unbroken, piling more of the same kind of atom on the surface will not affect the work function. For reference, one monolayer of copper has a surface density of approximately 2×10^{15} atoms/cm². As the atomic concentration of the contaminant film approaches a contiguous atomic monolayer, the addition of more atoms has a diminishing effect.

Figure 7 shows a work-function map of a doughnut-shaped section of the test wafer. As seen in the image, all six contaminated spots were detected. TXRF analysis was subsequently performed on the wafer to measure the atomic concentration of surface copper at all six spots. The copper concentration at site 1 was found to be 2.4×10^{11} atoms/cm². The CPD signal intensity at that spot was about 150 mV. This experiment demonstrates that even very low surface concentrations of copper can be detected

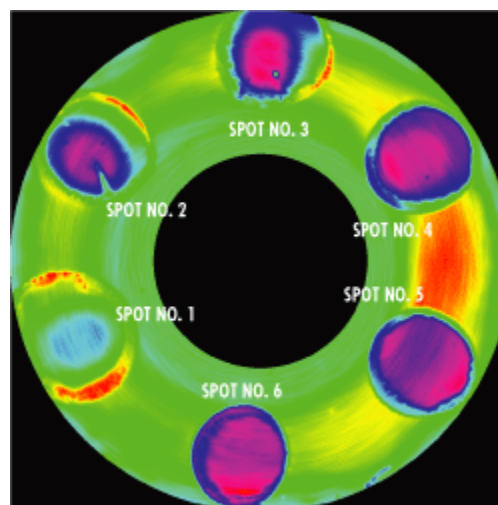


Figure 7: Wafer images of various copper residue concentrations taken using the nvCPD system.

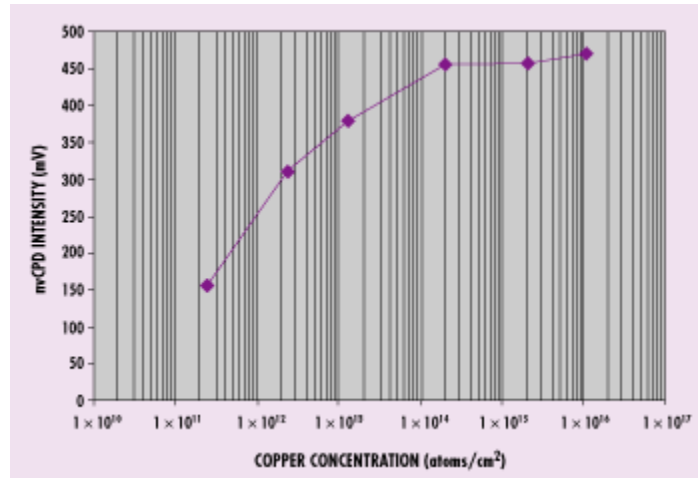


Figure 8: Correlation between the nvCPD signal and the concentration of copper surface contamination on a silicon wafer.

Conclusion

This article has presented data characterizing the ability of a novel wafer inspection technique to detect metal contaminants on a silicon wafer surface. Signal strength has been shown to be proportional to the difference in work function between the contaminant metal species and the underlying silicon. Signal strength has also been shown to be proportional to the surface concentration of the contaminant species in the range of 2×10^{11} to 1×10^{14} atoms/cm².

Because the nvCPD imaging technique can scan the entire wafer surface and is fast and sensitive to submonolayer amounts of surface contamination, it is useful for process characterization and control applications throughout the fab. While the data presented here deal with metal detection, the technique is also sensitive to minute amounts of other surface contaminant species, such as solvent and photoresist residues.

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