A NEW APPROACH TO SPATIALLY CONTROLLABLE CVD

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Abstract: This paper describes the continuing design evolution of a new approach to spatially controllable chemical vapor deposition for electronic materials manufacturing. Based on the success of a previous prototype reactor, we describe construction of a newer version of the prototype reactor system to assess its performance and identify its key operational characteristics. This new design includes a fully automated feed gas control system, allowing the reprogramming of reactor operation without hardware modifications and a time-shared gas sampling mass spectrometer for spatially resolved across-wafer gas composition analysis.

1. Introduction

The continuing reduction of device feature size, growing scale of device integration, expanding number of new electronic materials, and increasing substrate (wafer) size motivate development of the new chemical vapor deposition (CVD) processes necessary to sustain the advancement of microelectronic technology. However, process conditions for optimal material and device quality often do not meet the across-wafer uniformity requirements for manufacturing, forcing a tradeoff between product performance and manufacturing productivity.

Significant research effort has been directed towards improving growth uniformity of CVD by wafer temperature control; (Moslehi *et al.* 1992, Stuber *et al.* 1998, Kiether *et al.*1994). Preliminary studies of designs that allow radial modification to reactant gas composition also have been introduced, such as the segmented reactant gas delivery showerheads of Moslehi *et al.* 1995 and Theodoropoulos *et al.* 2000.

In this paper, we present a new approach to the control of gas phase composition in CVD, a design concept aimed at improving 2-dimensional across-wafer controllability. Preliminary experiments, modeling results, and design concepts were reported in [1]. In this paper, as a follow-up effort, additional design concepts endowing more flexibility and extendibility to the basic design and construction of new version of prototype Programmable CVD system are introduced. Also, results of the preliminary wafer temperature measurement experiments as a first step to assessing the performance of new prototype reactor are presented.

2. The Programmable Reactor concept

The major design feature of the Programmable CVD reactor is its segmented showerhead. The effect of the segmented showerhead design is to discretize the region above the wafer surface into individually controllable regions. Because each segment is fitted with separate feed gas lines, the precursor gas composition in the area of wafer surface corresponding to each segment can be individually adjusted by a flow control element in the gas distribution system.

In addition to this discretization, to enhance film uniformity and to reduce interaction between the volumes of gas on the wafer area segmented by the showerhead, residual gas is recirculated up through

each segment of the showerhead. This gas exhaust results in diffusional transport dominating in the gap between wafer surface and segment bottom. A linear motion device controls the vertical position of segmented showerhead assembly, providing direct control of the intersegment diffusional flux in the wafer/showerhead gap region. Thus, segment position is a critical parameter controlling the smoothness of the thickness profile across wafer surface. The distance between wafer surface and feed tube also can be adjusted, giving additional flexibility to reactor.

3. Prototype construction and testing

We successfully demonstrated the feasibility of this concept with an initial prototype reactor (P1) modified from a commercial CVD cluster tool [1], using tungsten CVD as a model deposition system. A typical tungsten film produced with the P1 reactor system and its thickness map are shown in Figures 1 and 2, respectively. In these experiments, 50 sccm of Ar, WF_6, H_2 were fed to segment 1, 2, 3, respectively and wafer/segment gap was set at 1mm.

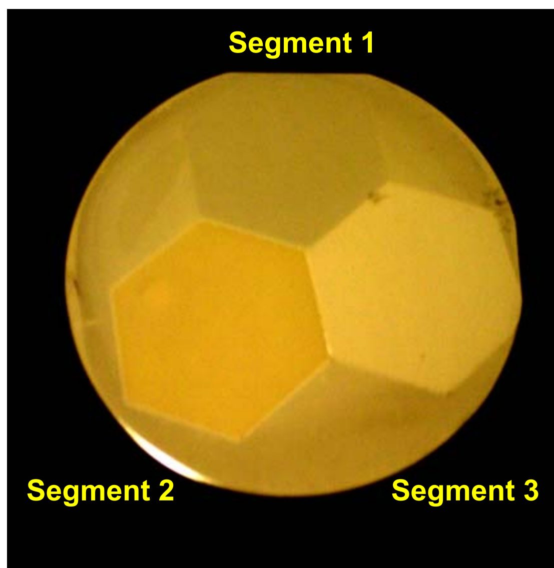

Figure 1. Typical tungsten deposition pattern produced by the prototype Programmable CVD.

Based on the success of preliminary test, we built and tested a new prototype reactor (P2) having a more flexible and extendible structure than prototype P1. Additional feed and sampling tubes were added to the showerhead to allow complete control of individual segment gas composition, and to allow sampling of gas composition within each segment. A drawing of P2 is shown in Figure 3.

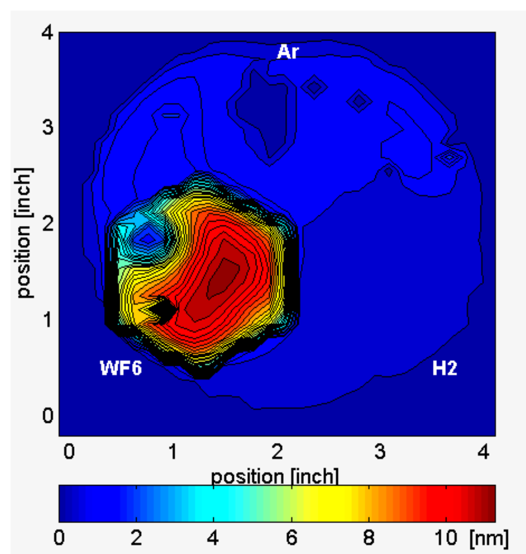

Figure 2. The thickness map of the wafer in Figure 1 measured by a high resolution 4-point probe.

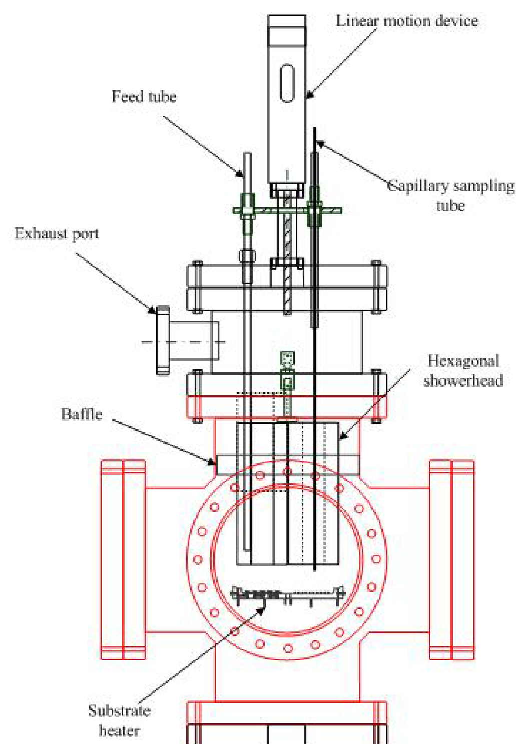

Figure 3. Programmable reactor, showerhead, heater, linear motion device and feed/sampling tubes.

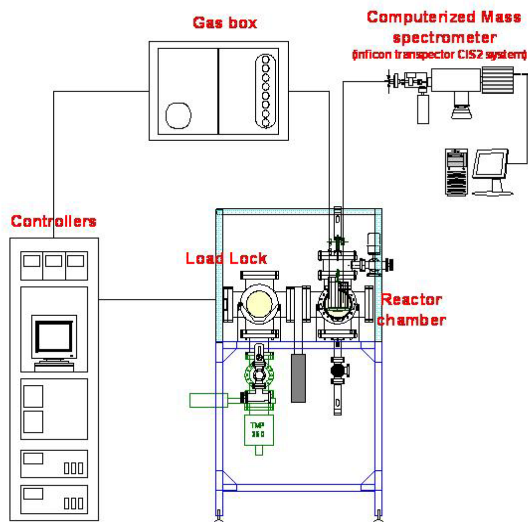

Figure 4. Schematic diagram of prototype programmable CVD system.

Figure 5. Picture of reactor and controllers.

The P2 system consists of four major components: reactor and loadlock equipped with pumps, gas box, controllers and gauge readouts, and the residual gas analysis system. The schematic diagram and pictures of controllers and chambers are shown in Figure 4 and 5, respectively.

The reactor and loadlock chambers are built with 8 inch six-way cross standard vacuum components. To minimize contamination and maintain UHV CVD conditions, each chamber is pumped downed with an individual set of turbo-molecular pumps backed up by rotary vane pumps. The primary component of the showerhead assembly is the honeycomb-shaped array of three segments machined from a single block of stainless steel. As designed, the three segments cover most of the surface area of the 4 inch wafers used in deposition experiments. Showerhead/wafer spacing is controlled with a linear motion device to control inter-segment region diffusion.

Each segment is fitted with two feed tubes and one sampling tube. WF_6 diluted with Ar is fed to one tube, H_2 to the other. The dilution capability of the new prototype system of WF_6 makes it is possible to decouple the total feed rate from the ratio of WF_6 and H_2 in each segment. The feed rates of these gases are controlled by individual sets of regulators, on/off valves and mass flow controllers. These flow control setups are managed by master control platform (Techware Brooks system) and built in stainless steel gas box for safety (Figure 6).

Figure 6. Gas box and its components.

4. Gas composition sensing

A novel approach to gas composition sampling is also implemented in P2. QMS (quadruple mass spectrometry) is one of the most widely used methods for in-situ real-time process monitoring. QMS instruments are compact and cost efficient as well as selective and sensitive. Also, because the mass spectrometer can directly sense gas

composition on specific point of reactor system without delay and disturbance to process performance, it is a candidate of sensor for real-time control. Recently, mass spectrometry has been shown to be successful for end-point detection and run-to-run control (Waits 1999 and Xu 2002).

Each Programmable Reactor segment is monitored individually with the QMS. Coupled with the reactor segment model described in [1], this capability of individual segment sampling and monitoring allows fast reprogramming of the recipe across the wafer surface using model based, real-time control or after a batch in a run-to-run control mode.

The sampling tube of each segment can be used to transport a small amount of gas to a real time in situ sensor, such as a mass spectrometer. From the residual gas analysis of each segment, approximate film thickness and the composition of film deposited on each area corresponding to each segment can be determined. For the sampling, an Inficon transpector CIS2 mass spectrometer is used.

To monitor gas phases in three segments pseudo-simultaneously during the operation, of the single mass spectrometer must have time-sharing capabilities. Three sampling tubes and on/off valves connect the segments to the mass spectrometer. Three on/off valves are sequentially opened and closed by control signal of Techware Brooks control platform to perform the mass spectrometer multiplexing. The schematic diagram of this setup is shown in Figure 7.

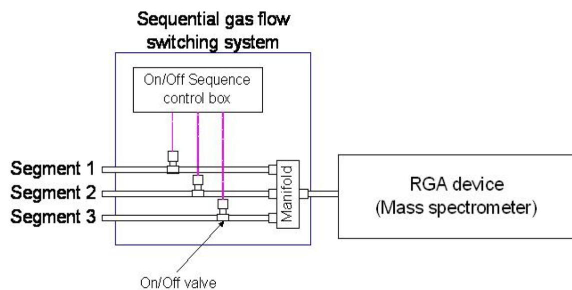

Figure 7. Schematic diagram of time-sharing RGA.

In addition to monitoring segment gas composition, the mass spectrometer sampling system has an additional sampling tube on the exhaust line for fault detection and chamber contamination monitoring. This sampling line consists of one ¼ inch stainless steel flexible tube equipped with a 35 micron orifice and bypass line (without orifice), for high pressure (above 1 torr) and low pressure operation, respectively.

5. Temperature distribution measurement

Wafer temperature is the other key factor affecting film growth uniformity in most CVD processes. To reveal the key parameters effecting wafer temperature and its uniformity, temperature measurement experiments were performed with an instrumented wafer over a range of operating conditions and reactor geometries.

With a thermocouple instrumented wafer, temperatures of 13 specific points are measured. In the Figure 9, the positions of 13 thermocouples and their relationship to the segment positions are shown.

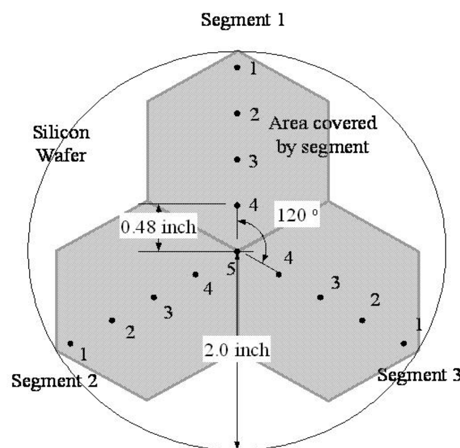

Figure 9. The position of thermocouples on the wafer and segments position.

It is believed that thermal conductivity differences between different mixture gases of each recipe may result in non-uniformity of wafer temperature. In order to assess this gas composition effect, the wafer temperatures are measured when the chamber filled with typical reactant gases (Ar, N_2, H_2) at 1 torr and a high vacuum condition at 400 ^oC heater setpoint. To minimize the other effects such as segment position, the segment assembly was lifted up to the highest position (32 mm from wafer

surface). The temperature measurement results of this experiment are shown in Figure 10.

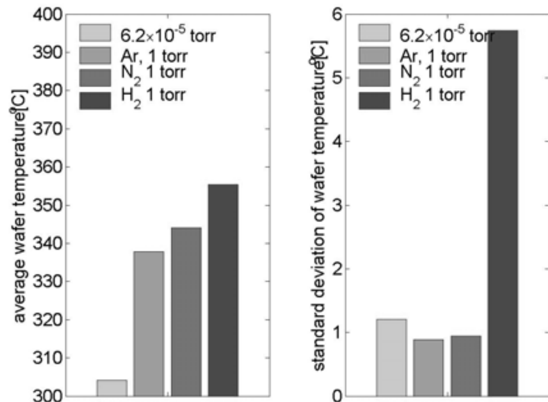

Figure 10. Wafer temperature when the reactor is filled with different gases (Ar, N_2, H_2) at 400 °C heater setpoint.

As can be seen in this figure, significant temperature differences for different operating conditions are observed. The largest temperature difference between each case was about 20°C except at the high vacuum condition (below1.0×10^{-3} torr). The heat conduction through the gas phase between the heater surface and wafer bottom causes higher wafer temperatures relative to those observed in the high vacuum case. When reactor is filled with H_2, temperature uniformity is much worse than the other cases. Considering non-uniform temperature distribution of the heater surface, non-uniform wafer temperature is due to the closer thermal coupling between the wafer and heater because of the higher thermal conductivity of H_2.

The physical geometry of the reactor components also relates to wafer temperature because radiation and heat conduction to the showerhead constitutes a major heat loss from the wafer surface. To assess these effects, we measured the wafer temperature with varying gap size. For this second experiment, heater temperature was set at 400°C and the gap size was changed from 5mm to 32mm under high vacuum conditions and at 1 torr pressure for three different gases (Ar, H_2, N_2).

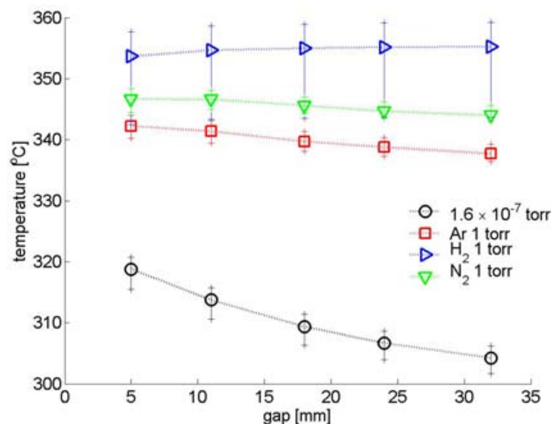

Figure 11. Mean wafer temperature with varying the gap size of segment, at 400°C heater setpoint.

As shown in Figure 11, average temperature differences were less than 10°C in the cases where the reactor is filled with gas. Under high vacuum conditions, temperature decreases with increasing gap size and the gradient of wafer temperature is larger than cases where the reactor is filled with gas. The reason for the decreasing temperature in the high vacuum case is that higher positions of the segment assembly allow the wafer to face an increasing area of cool reactor wall, resulting in additional wafer heat loss, an effect obscured by the thermal conductivity heat transfer in the non-vacuum cases.

6. Concluding remarks

The Programmable Reactor system described in this paper has far greater spatial controllability than typical commercial CVD reactor designs. One of the most important applications of this spatial controllability is the fast reprogramming from one operational mode to another, a capability which reduces the time and cost of finding the proper recipe for uniform films of desired thickness and composition. The strategy of reprogramming to find the recipe is briefly described in Figure 12. When different recipes of gas are fed to each segment and the gap set to its minimum (nozero) value, it is possible to deposit different films in a single batch producing a library wafer. Following deposition, offline metrology is used to analysis each segment

region on the wafer surface, and the relationship between film properties and operating conditions is determined from the on-line measurements taken during the production of the library wafer. The recipe can be used as is, or one can be derived by interpolation between library wafer regions, to be sent to all segments to produce uniform film across the wafer, opening the door to combinatorial CVD studies and other novel modes of operation in a single CVD reactor system.

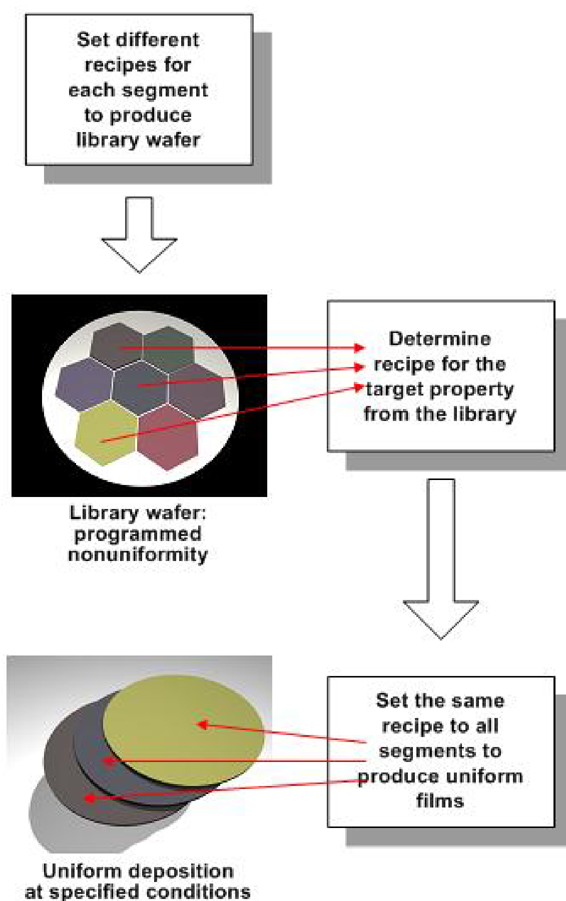

Figure 12. Fast reprogramming for materials and process discovery.

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