Title

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Conformal Deep Trench Coating with both Conducting and Insulating Materials

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Abstract

A thin film coating system has been developed for deposition of both conductive and insulating material. The system employs an RF discharge plasma source with four straight RF antennas, which is made of or covered with the deposition material, thus serving simultaneously as a sputtering target. The average deposition rate of the copper thin film can be as high as 500 nm/min when operated in CW mode. Film properties under different plasma conditions have been investigated experimentally. By adjusting RF power, gas pressure, duty factor, and substrate biasing conditions, several thin film coating schemes can be achieved, one of which has been demonstrated to be suitable for conformal deep trench coating. Conformal coating over trenches of high aspect ratio (>6:1) has been demonstrated at both micron and submicron scales.

I. INTRODUCTION

Conformal trench coating is of great interest in areas such as IC fabrication (interconnect wiring fabrication), micro-electromechanical systems (MEMS) and nano-slit nano-tunnel fabrication. In the area of microelectronics, a search is underway to find a reliable technique for filling trenches and vias using copper metallization technology. Due to the need for further decrease of the line width and the via area in ULSI application, vias with aspect ratios of approximately four have to be filled completely[1]. Therefore, conformal coating continues to be a growing need in the microelectronics industry. Physical vapor deposition (PVD) techniques, especially magnetron sputtering, have been widely used for thin-film deposition in microelectronics. However, the conformality of films from the conventional magnetron sputtering deposition process is poor due to a great deal of self-shadowing. Shadowing effects can cause, for example, poor step coverage on sidewalls and bottoms of trenches and vias, and can form overhanging structures on the top corners of the trenches and vias. These effects can lead to void formation when attempting to fill a surface feature[2]. Thus CVD-based techniques, which are able to fill trenches and vias with a high aspect ratio[3], are preferred. However void creation can still be observed, due to non-uniform layer growth. In addition, the deposition technique and the chemistry make their application much more difficult.

Some prior research has also shown that if the sputtered atoms are highly ionized, it will be very useful to control the film properties with the aid of the ionic charge and/or the kinetic energy of the ionized sputtered atoms[4-6]. High ionization rate of the sputtered atoms is a very important requirement in directional sputter deposition, which is often used in high aspect ratio deposition applications[7].

In this paper, a new PVD system is described that has been used to produce and investigate thin film configurations under different plasma operation conditions. Conformal coating of trenches with high aspect ratio has been achieved.

II. EXPERIMENTAL SETUP

An RF-driven sputtering system[8] has been developed at Lawrence Berkeley National Laboratory for conformal coating of both metallic conductors such as Cu, Al, Pd etc. and insulators such as Diamond-like carbon (DLC). As shown in the schematic diagram (Figure 1a), the system is equipped with an RF power supply, a matching network, and a coating chamber with four RF antennas connected in parallel. These antennas also serve as sputtering targets. Each antenna consists of a water-cooled target tube, which is made of or covered with the coating material, and quartz shielding sleeve. A photograph of the system is shown in Figure 1b.

The substrates are located in the center of the coating chamber, surrounded by the sputtering targets, where the plasma has the highest intensity and is the most uniform. For coating metal species, for instance copper, argon gas is introduced in the chamber and high-density argon plasma is generated. Due to the electrode-size effect, the RF antenna is self-biased at a relatively large negative voltage. The argon ions in the plasma sheath, driven onto the antenna surface by this voltage, sputter off the metal material on the antenna. Metal atoms sputtered from the targets will diffuse into the plasma. Since the ionization potential for most metal species is lower (e.g. 6~7 eV) than argon (15.8 eV), the metal atoms are easily ionized in the high-density argon plasma. A great percentage of the neutral atoms are ionized in the high-density plasma and finally a thin film of copper is formed on the substrate. A large ion to neutral ratio can be achieved with this coating system, which is mainly controlled by the RF power and gas pressure.

III. RESULTS AND DISCUSSTION

a. Deposition rate and film structures under various coating conditions

A deposition rate of up to 500 nm/min for copper can be achieved in CW mode with this coating system. The deposition is controlled mainly by the RF power, gas pressure, and duty factor (in pulse mode). The microstructures of the thin film depend on the deposition parameters and local topography. Therefore, the deposition techniques required for successful coatings of a high aspect ratio feature have to be carefully optimized. An experimental study has been carried out to investigate the effect of the coating parameters on the film microstructure. As illustrated in Figure 2a, at relatively low RF power and low gas pressure (coating condition 1), the metal ions approach the sidewalls at high oblique angles. Due to shadowing effects, film on the sidewalls is in the form of columnar, porous structures. In addition, due to atomic-attraction forces, the incident atoms are preferentially deposited on the top corners of the hole. This again gives rise to overhangs at the top corners. At higher pressure and lower RF power (coating condition 2), the metal neutrals and ions undergo a lot more scattering before reaching the substrate, which greatly enlarges the angular distribution of the flux. As a result, the chance for porous-like film to grow is reduced and the film becomes much denser but the flux directionality is sacrificed. The schematic diagram of such a concept is shown in figure 2b. Under this coating condition, the top surface of the vias and trenches can be shrunk and closed up very quickly, however, leaving the bottom unfilled. This coating condition may be useful for forming nano-pores and nano-slits. Since the angle of incident flux is very important for the conformal coating of narrow trenches, this coating scenario still doesn't work well for high aspect ratio coatings. The most ideal coating condition for high aspect ratio coatings is found to be at high RF power and low gas pressure (coating condition 3). As illustrated in figure 2c, at low gas pressure, the scattering of the Cu ions and neutrals is highly reduced; highly directional flux can go through the deep trench with fewer interactions. In addition they can maintain relatively high kinetic energy because they undergo less scattering that would slow them down. The plasma density is higher at high RF power, which results in a bigger voltage across the plasma sheath both around the sputtering target and the coating sample. As a result, the energy of the metal ions and the neutrals is higher. They can generate more re-sputtering of the deposited film while traveling through the trench, once again increasing the uniformity and conformality of the film.

In figure 3, some experimental results are shown. The SEM image in figure 3a shows that with the coating condition 1 discussed above, film formed near the top corner of the via has a porous and columnar microstructure. Figure 3b indicates that under coating condition 2, the film is much denser and uniform. A hole with a diameter of a few hundreds of nanometers can be shrunk to a much smaller nano-pore within an hour.

b. Conformal coating of trenches with high aspect ratio

Conformal coating of trenches with high aspect ratios has been achieved using the coating condition 3 described above. The substrate is a (1 0 0) oriented p-type Si wafer. Two sets of patterns are prepared on the substrate. One set is patterned with high aspect ratio trenches using the STS reactive ion etching (RIE) equipment. The widths of the trenches range from 1μm to 4μm, and the aspect ratios range from 20:1 to around 6:1. The other set of patterns have much smaller sizes, which range from 80 nm to 150 nm. The aspect ratio is about 18. SEM pictures of conformal coating patterns are shown in Figure 4. A layer of copper film with a thickness of 600 nm is coated around a 4-μm-wide silicon trench, the aspect ratio of which is 6:1. High conformity has been achieved. The coated film follows the topology of the trench fairly well and exhibits a high degree of uniformity. This coating condition also works very well at a much smaller scale of trench size. Figure 5 shows the SEM images of the cross-section of a 110 nm-wide trench with and without copper film coating. The aspect ratio is as high as 18:1. After the deposition, the trench width is reduced to 60 nm.

c. Coating with insulating material

By changing the antenna covering material from copper to graphite and, at the same time, introducing both CH_4 and argon mixed gas to generate plasma, DLC thin film can be formed on the substrate. Under 400 w of CW RF power, a 200 nm-thick DLC film is formed after a 30 min coating time.

Diamond-like carbon (DLC) films are of considerable research interest because of their widespread applications as protective coatings in areas such as optical windows, magnetic storage disks, automobile parts, biomedical coatings and MEMS devices.

IV. SUMMARY

A new coating system for conformal deposition of both conducting and insulating materials has been developed. Film properties under different plasma conditions have been investigated experimentally. By controlling RF power, gas pressure, duty factors (pulse mode), several thin film coating schemes have been developed and experimentally tested, one of which proved suitable for conformal deep trench coating. There are also other important factors that can affect the film quality and conformality, such as substrate biasing conditions, substrate temperature etc. These effects are the subject of further experimental study.

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Figure Captions:

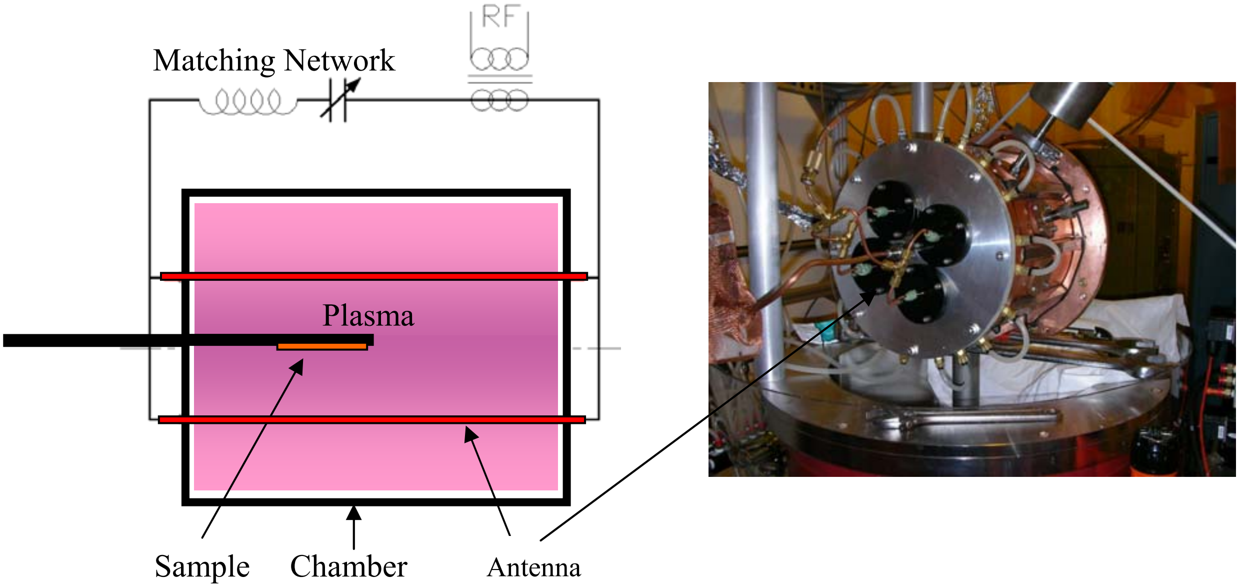
Figure 1: (a) Schematic diagram of the coating system; and (b) A photograph of the coating system.

Figure 2: Schematic diagram of the film microstructure under coating condition of (a) low pressure and low RF power; (b) high pressure and low RF power and (c) low pressure and high RF power.

Figure 3: (a) SEM image of the copper thin film grown under coating condition 1 (low gas pressure and low RF power); (b) 350 nm diameter hole drilled by FIB (top) and the hole is shrunk to 13 nm in diameter by thin film deposition and coating condition 2 (high gas pressure and low RF power) (bottom).

Figure 4: SEM pictures of the cross-section of a conformal coating on a 4 μm wide trench; the aspect ratio of the trench is around 6:1 (left). And zoom in of the cross-section. (right)

Figure 5: SEM pictures of the cross-section of a conformal coating on a 110 nm wide trench; the aspect ration of the trench is 18:1. (a) cross-section of the trench without copper film coating; (b) cross-section of the trench with copper film coating.



(a) (b)

Figure 1

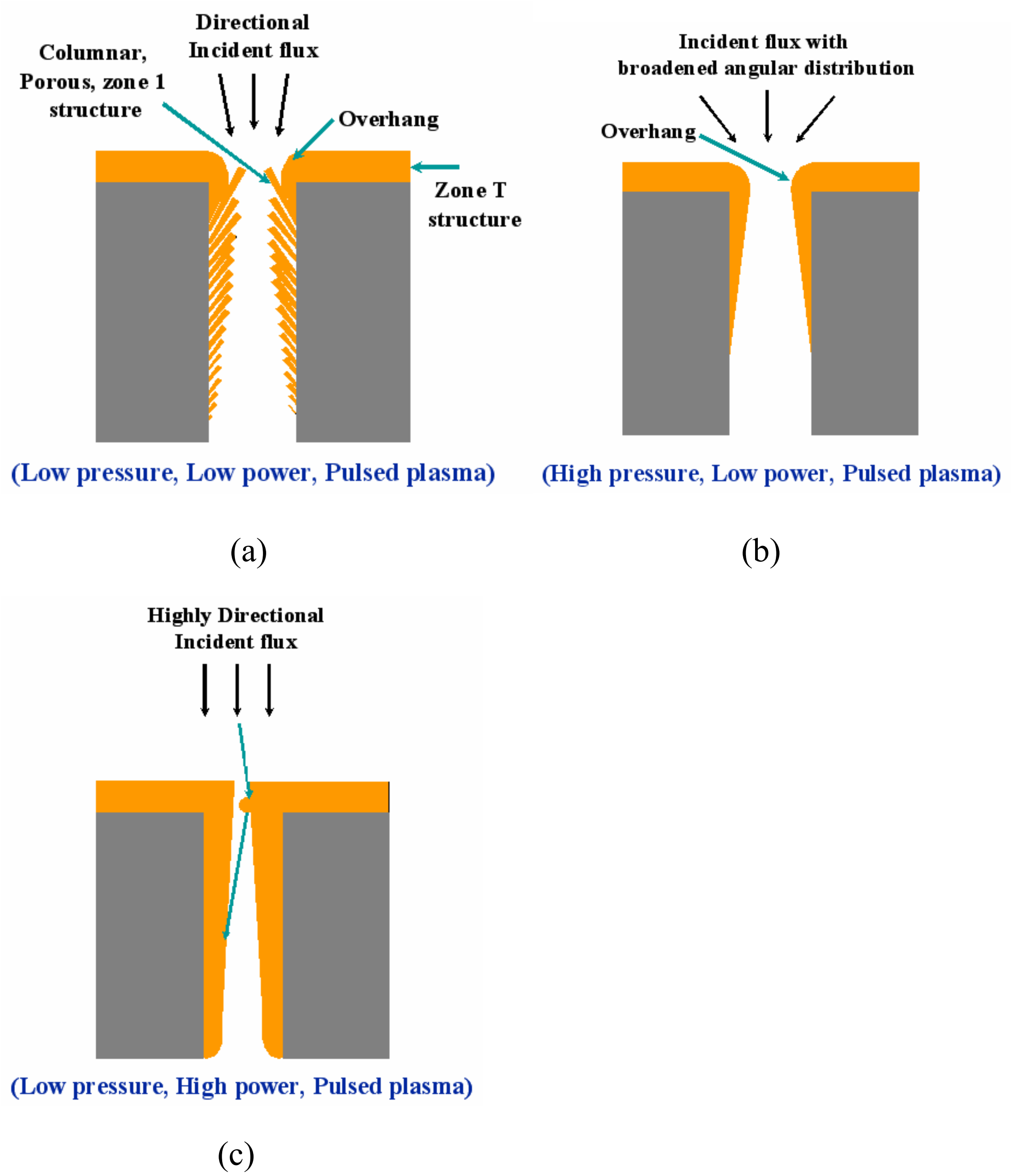
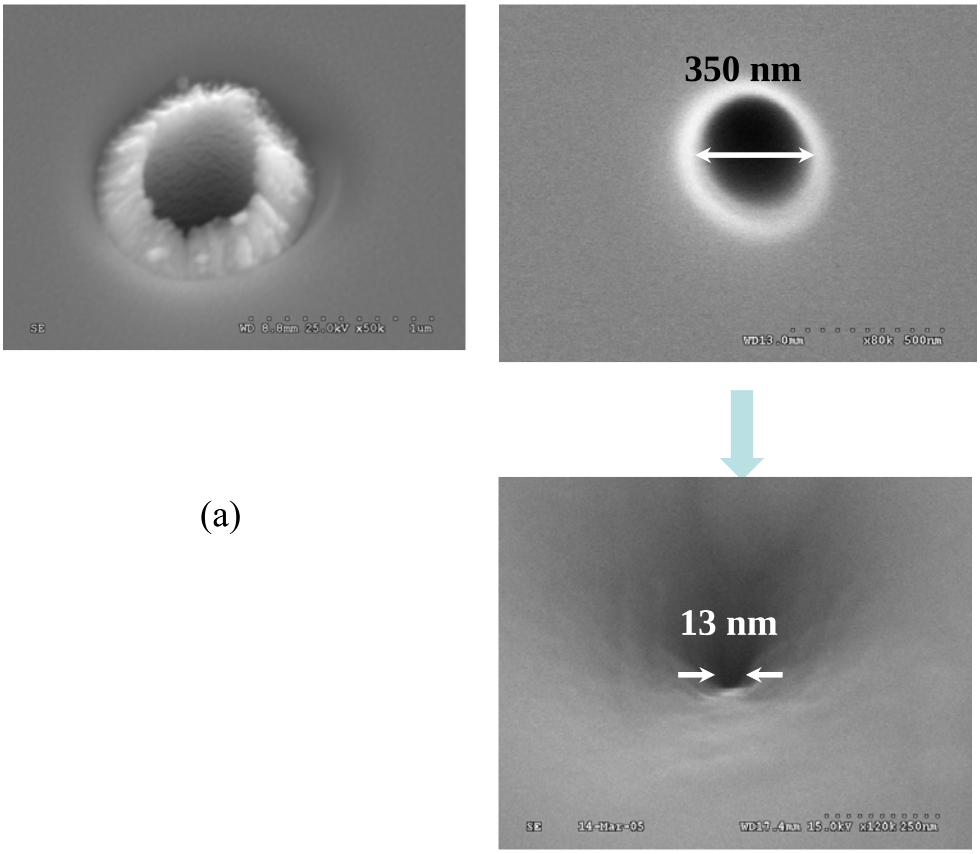

Directional
Incident flux
Columnar,
Porous, zone 1
structure
Overhang
Zone T
structure
(Low pressure, Low power, Pulsed plasma)
(a)
Incident flux with
broadened angular distribution
Overhang
(High pressure, Low power, Pulsed plasma)
(b)
Highly Directional
Incident flux
(Low pressure, High power, Pulsed plasma)
(c)

Figure 2


SE
WD 8.8mm 25.0kV x50k 1um
350 nm
WD13.0mm x80k 500nm
13 nm
SE 14-Mar-05 WD17.4mm 15.0kV x120k 250nm

(a)

(b)

Figure 3

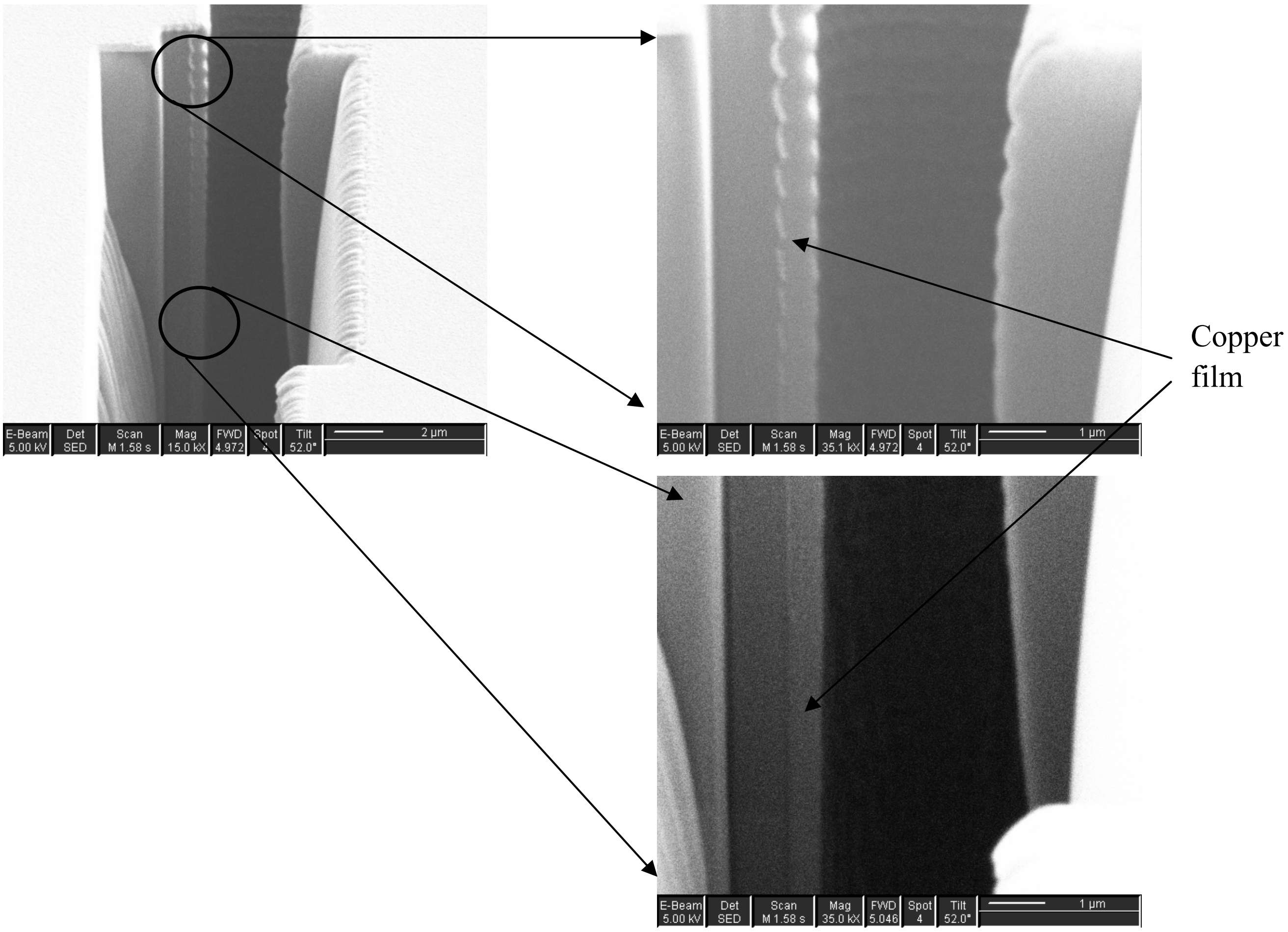
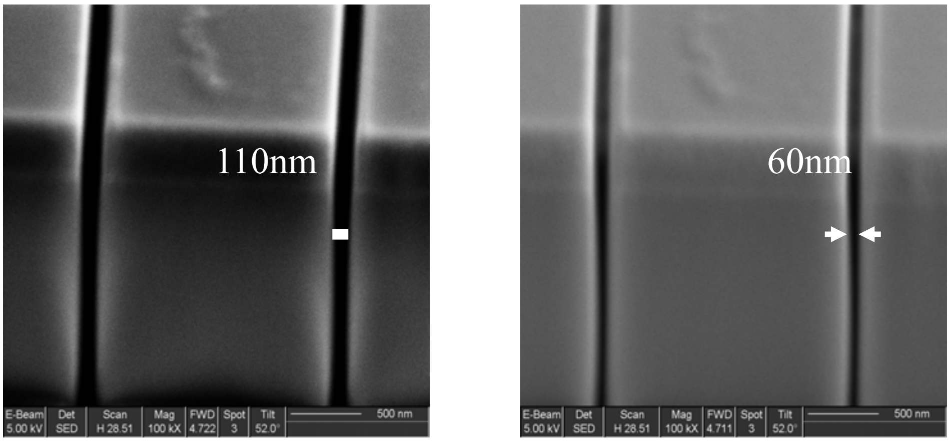

Copper film
E-Beam 5.00 kV
Det SED
Scan M 1.58 s
Mag 15.0 kX
FWD 4.972
Spot 4
Tilt 52.0°
2 µm
E-Beam 5.00 kV
Det SED
Scan M 1.58 s
Mag 35.1 kX
FWD 4.972
Spot 4
Tilt 52.0°
1 µm
E-Beam 5.00 kV
Det SED
Scan M 1.58 s
Mag 35.0 kX
FWD 5.046
Spot 4
Tilt 52.0°
1 µm

Figure 4


110nm
E-Beam 5.00 kV
Det SED
Scan H 28.51
Mag 100 kX
FWD 4.722
Spot 3
Tilt 52.0°
500 nm
60nm
E-Beam 5.00 kV
Det SED
Scan H 28.51
Mag 100 kX
FWD 4.711
Spot 3
Tilt 52.0°
500 nm

(a) (b)

Figure 5