

Gas Delivery and Virtual Process Chamber Concept for Gas Assisted Material Processing in Focused Ion Beam System

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ABSTRACT

Gas Assisted Etching (GAE) and material deposition using gaseous precursors have become a critical part of Integrated Circuit (IC) modification and other applications of Focused Ion Beam (FIB) systems. Widely used methods of gas injection in FIB systems are either needle type or shroud type gas delivery nozzles. Each of these methods of gas delivery has significant drawbacks. Release of the gas from the needle type nozzles detrimental for the vacuum level in main chamber of the system, as the gas quickly dissipates from the process area. Insertion of shroud concentrators into the primary ion beam path the secondary electron path leads to significant decline in S/N ratio of the FIB image. Proposed “*CUPOLA*” geometry of the gas delivery nozzle would allow to concentrate process gas in the area of interest, as it is currently done by shroud concentrators, and, according to secondary electron trajectory simulations, would significantly improve signal level of secondary electron image, as compared to shroud concentrators.

INTRODUCTION

Optimized gas-assisted processes are critical for effective utilization of the Focused Ion Beam (FIB) systems in industrial applications¹, including semiconductor circuit modification, or circuit edit, and FIB machining of the silicon and diamond-based tips for Atomic Force Microscopy (AFM). Shrinkage of the IC feature dimensions to below 100 nm drives a growing interest in gas assisted focused electron beam processing and nanoscale deposition², where optimal gas delivery would also be critical.

Reported in literature optimal precursor pressure levels for gas-assisted FIB etching processes are in the millitorr range. For example, measurements by Ochiai et al. indicated³, that the optimal Cl₂ pressure for FIB assisted etching of GaAs is in 20 mTorr range and the optimal XeF₂ pressure for FIB assisted etching of Si is close to 1 mTorr. Design of the modern FIB systems however, requires maintaining much lower pressure level in the main chamber of the system, typically $\sim 2 \times 10^{-5}$ Torr⁴ or below, in order to achieve reliable operation. These conflicting pressure requirements create difficulty to operate at the optimal level of precursor gas pressure.

Group of Ochiai et al. used separately pumped subchamber³, filled by the precursor gas and coupled to the main chamber of the FIB system only by the small orifice for passing primary ion beam and secondary electron signal, to study precursor

pressure dependence of gas assisted FIB milling. Folch et al. also utilized precursor-filled subchamber⁵ to construct “EBD cell” for the study of electron beam induced deposition in SEM. While the subchamber approach to gas delivery is a convenient experimental setup, it is not used extensively in industrial FIB systems at this time.

Capillary needles are the most commonly used method of delivery the gas close to the area of interaction between the ion or electron beam and the sample⁶. Nevertheless gas is released from the needle close to the surface of the sample it quickly dissipates from the work area, creating significant gas load in the main chamber of the FIB system.

Shrouded-type gas concentrators⁷, such as “*Beehives*”⁸ and similar, are used today in commercial FIB systems to create high localized pressures of process gas for bulk material removal applications. High accuracy milling work, including the via milling, is also possible with the shroud concentrators and can be done with reduced level of the base pressure in a main vacuum chamber of the FIB system⁹. Unfortunately, introduction of the shroud concentrator into the path of the primary ion beam and the path of the secondary electrons significantly reducing the level of a secondary electron signal available for imaging. Poor imaging capability is a limiting factor for use of the “beehive” nozzles and other shroud concentrators in precision FIB applications.

Previous experimental work demonstrated¹⁰ that contrast level of the secondary electron signal, collected through the “beehive” nozzle, can be increased by up to factor of eight by biasing the nozzle positively, relatively to the potential of the system chamber. The S/N level of the image however remained too low for the high quality imaging of the small features. Improved gas delivery method is needed to optimal precursor pressure regime for the gas assisted charged particle beam processes with acceptable quality of through-nozzle imaging of the area of interest.

VIRTUAL CHAMBER CONCEPT DESCRIPTION

There is a long-settled agreement in literature^{11, 12} that the angle of departure of the gas molecule after the interaction with the solid sidewall of the chamber in vacuum is following a cosine distribution and that the most probable departure direction for the molecule is orthogonal to the wall plane.

Interesting consequence of this departure angle distribution is that highly polished cylindrical or spherical surfaces could potentially have increase local pressure at the center of the sphere or along the axis of the cylinder. Nesterov et al. calculated¹³, that local pressure at the center of the spherical vacuum vessel can be by factor of seven larger then the pressure at the vessel walls.

It becomes logical therefore to make an end of the gas delivery nozzle semi-spherical in shape (**Fig. 1**) and position the process area at the center of semi-sphere. In this configuration, area of a relatively high precursor gas pressure is confined within the virtual processing chamber, created between the semispherical end of the gas delivery nozzle and the surface of the sample. The delivery tube, supplying precursor gas to the

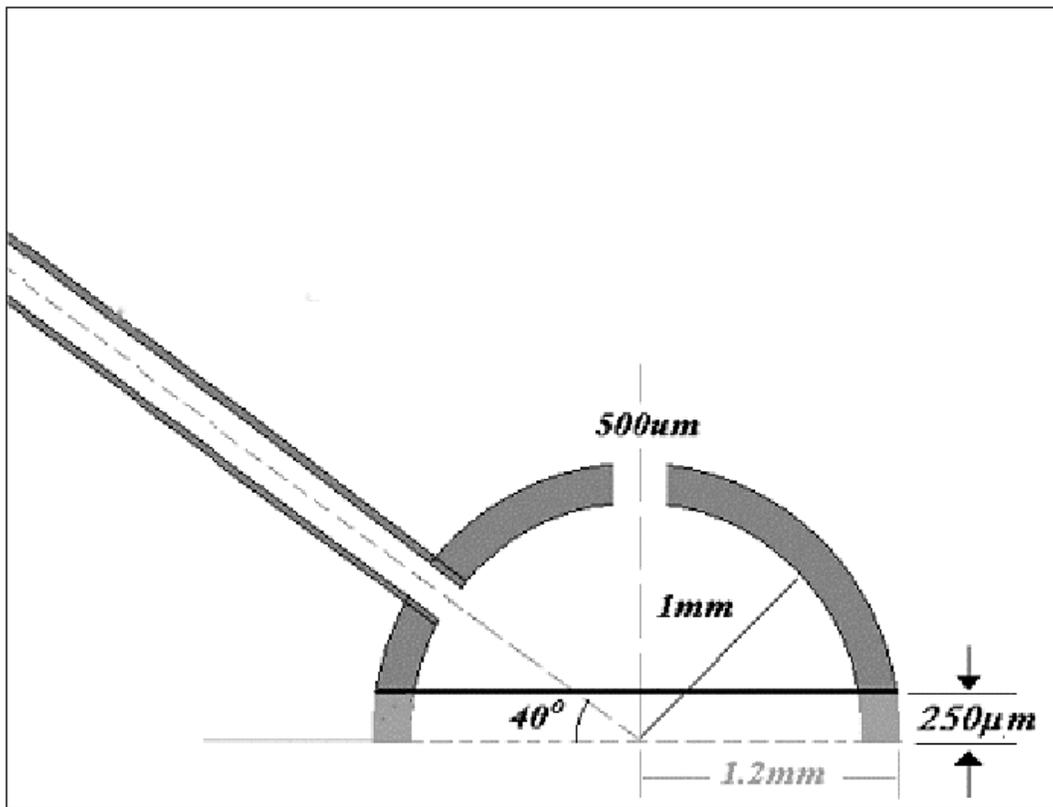


Fig. 1 Virtual process chamber concept, comprising of semi-spherical attachment at the end of gas delivery nozzle

virtual processing chamber, is directed to the location of interaction between the primary particle beam and the sample at the center of the semi-sphere, to take additional advantage of the directionality of the molecular gas flow exiting the supply tube¹⁴. The length of the straight portion of the delivery line, directed toward the center of the virtual processing chamber, should be much longer than the diameter of the tube.

“*CUPOLA*” gas delivery nozzle (**Fig. 2**) is designed as a practically realizable implementation of the virtual process chamber concept. It is intended for high-throughput operation of industrial FIB system in semiconductor circuit modification and AFM tip manufacturing applications.

The nozzle should be aligned within the FIB apparatus in such a way that, while the nozzle is extended, the primary ion beam would pass through the center of the 500 μm aperture at the top of the nozzle. Circular bottom opening of the nozzle should be parallel to the sample plane and internal surface of the “*CUPOLA*” may need to be highly polished, to ensure that the internal surface of the nozzle is semi-spherical on the microscale.

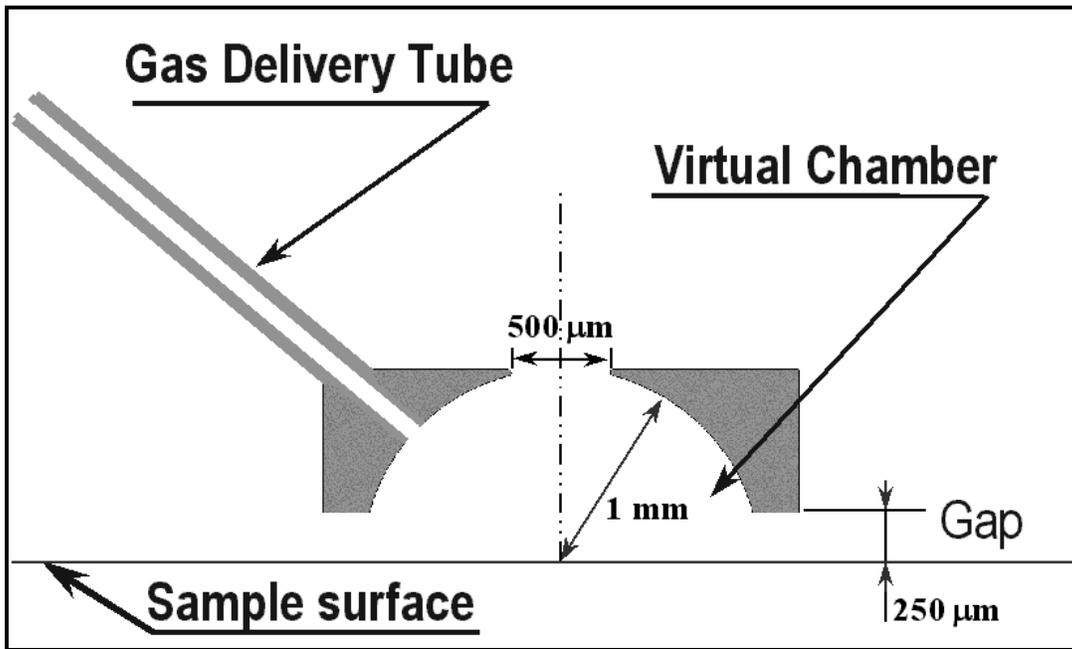


Fig. 2 “CUPOLA” nozzle designed as a practical implementation of the virtual process chamber concept.

ELECTRON OPTICS SIMULATIONS

In order to make a comparative evaluation of the imaging capabilities of proposed “CUPOLA” nozzle design in respect to the imaging capabilities of the existing shroud gas concentrators (Fig. 3) a rotational-symmetric models of both nozzle configuration were

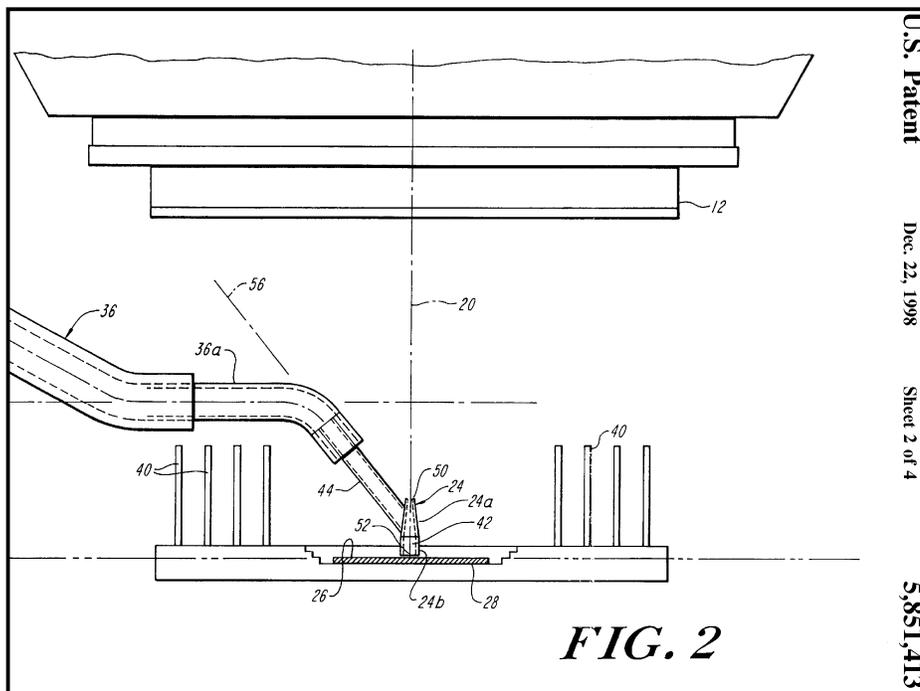


Fig. 3 Shroud, or “Beehive”, nozzle presented on Fig. 2 in US Patent 5,851,413

compared in LORENTZ-2E particle trajectory simulation software from Integrated Engineering Software Company, Manitoba, Canada.

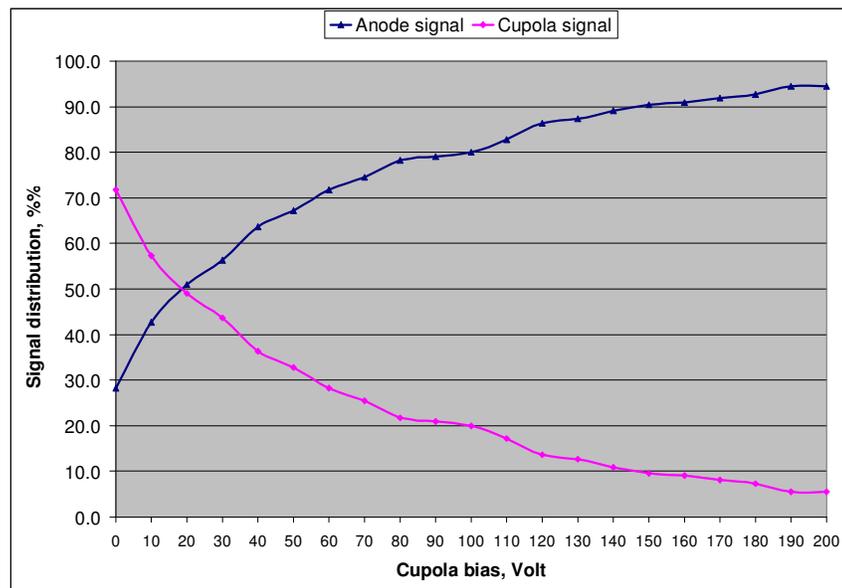
Geometry of the “CUPOLA” nozzle was modeled after the Fig. 2. For the shroud, or “Beehive” nozzle, 2 mm width of the opening directed toward the sample was assumed to for the purposes of comparison with the “CUPOLA” design and the remaining dimensions of the shroud concentrator were calculated based on the proportions of the Fig. 3 representation of the shroud. Resulting overall height of the shroud was calculated as 9.18 mm and width of the opening at the top of the shroud calculated as 0.59 mm.

Both nozzle models were placed on 250 μm distance from the surface of the sample. The surface of the sample, for the purposes of simulations, was assumed to be conductive and grounded. Simulated electron emission was launched from 5 μm above the surface of the sample on the axis of symmetry of each of the nozzle models with initial electron energies of 1, 2, 3, 4, 5, 7, 9, 11, 13, and 15 electron volts. Electrons with each level of energy were launched in 11 beams, equally distributed within ± 45-degree angle from the axis of symmetry of the models. Potential of both nozzles was varied from zero to two hundred volts, to evaluate possibility of the enhanced extraction of the electrons through the top aperture of the nozzle. Collection electrode, or anode, was placed on the distance of 40 mm from the surface of the sample and set to +400 Volt potential.

SIMULATION RESULTS AND DISCUSSION

Results of the of the electron trajectory simulations were evaluated in terms of the ratio between the number of the electrons that successfully pass through the top of the nozzle and collected by the anode, to the number of the electrons that are captured on the internal surface of the nozzle. The results of evaluation are represented by the graphs on Fig. 4 for the “CUPOLA” and Fig. 5 the shroud, or “Beehive”, nozzles respectively.

Fig. 4
‘CUPOLA’
simulation
results.



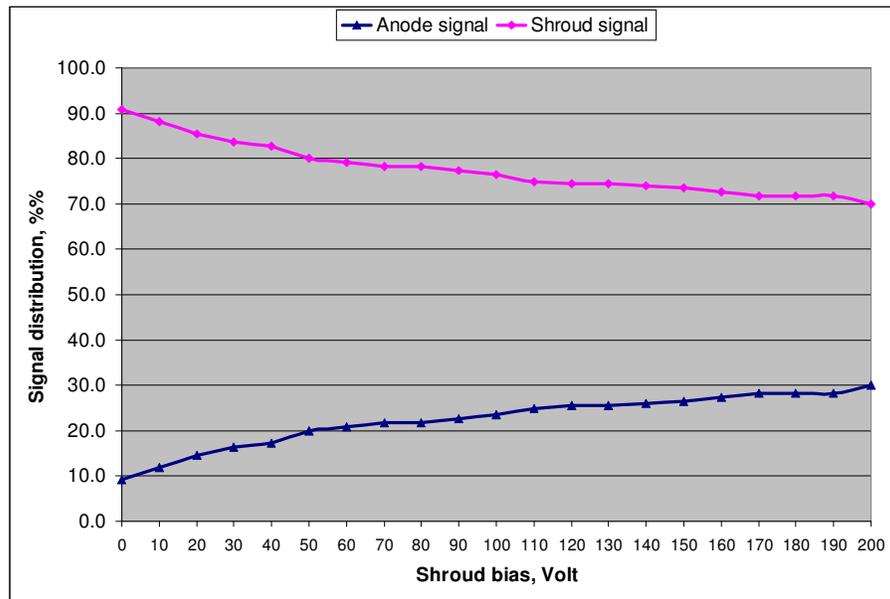


Fig. 5
Shroud, of
‘Beehive’
simulation
results.

Even at the zero volts nozzle potential, corresponding to the grounded nozzle configuration, 28% of the simulated secondary electrons exit the “CUPOLA”. With the “Beehive” nozzle configuration only 9% of the simulated secondary electrons are exiting the grounded nozzle and collected by the anode.

Increase of the “Beehive” nozzle potential results in a slow increase of the fraction of secondary electrons passing through the top of the nozzle, reaching the 30% of the simulated secondary electrons collected by the anode at + 200 Volt potential applied to the “Beehive” nozzle. As much as 70% of the electrons are still captured by the nozzle (Fig. 6).

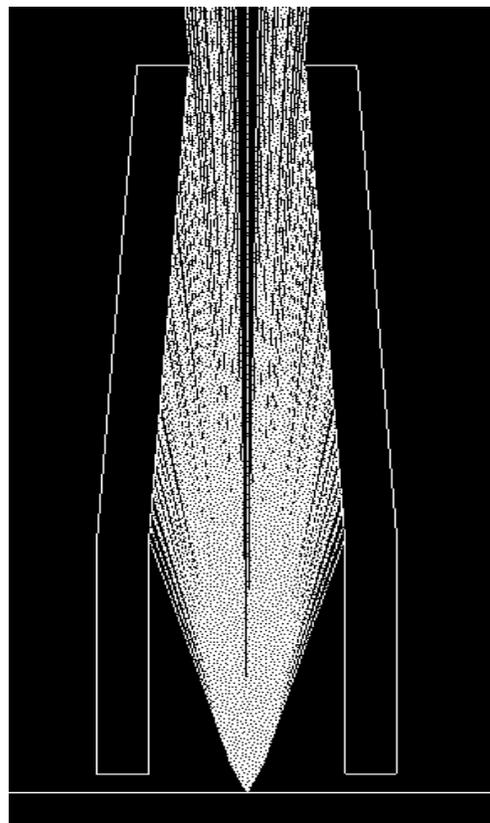
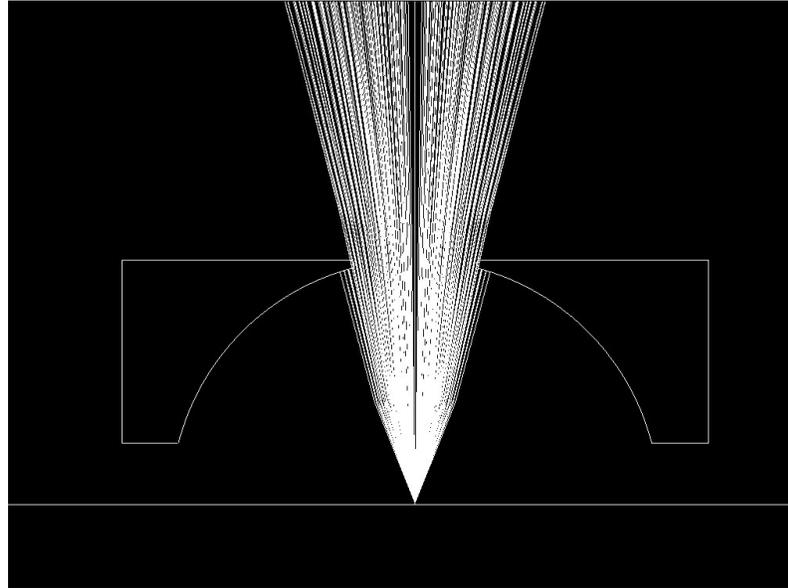


Fig. 6
Modeled trajectories of the secondary electrons, extracted through the positively biased ‘Beehive’ gas delivery nozzle under +200 Volt nozzle bias potential. Most of electrons are absorbed by the internal surface of the shroud.

Increase of the “*CUPOLA*” nozzle potential results in a much stronger increase of the fraction of secondary electrons passing through the nozzle, reaching 94.5% of simulated secondary electrons collected by the anode at + 200 Volt potential applied to the “*CUPOLA*” nozzle. Slightly over 5% of the secondary electrons remain captured by the nozzle (Fig. 7).

Fig. 7

Modeled trajectories of the secondary electrons, extracted through the positively biased “*CUPOLA*” gas delivery nozzle under + 200 Volt nozzle bias potential. Most of electrons are extracted through the aperture at the top of the “*CUPOLA*” nozzle.



It is evident from the secondary electron simulation results, that a fraction of the secondary electrons, generated by the interaction between the primary ion beam and the material of the sample during the gas assisted etching process, is collected by the gas delivery nozzle itself. This observation sets basis for the future experimental investigation of possibility to detect material-dependent transitions of the secondary electron emission during the FIB milling process by monitoring the nozzle-absorbed current. Such detection could have applications in via milling endpoint application, similarly to the sample absorbed current, or “stage current” endpoint techniques ^{15, 16}.

Current simulations did not investigate effects of interactions between the secondary electrons and the high-pressure gas within the “*CUPOLA*” nozzle. It is evident from the nozzle design however, that the path of the secondary electrons in the high gas pressure region within the “*CUPOLA*” nozzle, which is about 1 mm distance, is significantly shorter then the path within the “*Beehive*” or other shroud nozzle, which is close to 9 mm distance. Signal degradation due to high gas pressure region within the nozzle should therefore be reduced in the “*CUPOLA*”, comparatively to shroud design.

CONCLUSIONS

Proposed virtual chamber concept and the “*CUPOLA*” nozzle design is expected to allow carrying gas assisted processes in FIB and other focused particle beam systems under the increased process gas pressure, previously available only with shroud concentrators, but with significantly improved secondary electron image signal level, as compared to “Beehive” nozzle and other shroud-type gas concentrators.

Electron trajectory simulations suggest that considerable fraction of secondary electron signal is absorbed by the gas delivery nozzle, creating a ‘nozzle absorbed current’. Detection of transitions in the nozzle current could have practical applications in FIB via milling endpoint detection application, similarly to the sample absorbed current technique.

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