

Chapter 13

Conclusions

A novel materials processing pathway, Directed Vapor Deposition, has been designed, constructed, demonstrated to work, and experimentally explored as a method for creating thick and thin film materials from the vapor phase in a distinctly different manner than possible with existing physical vapor deposition systems [142, 186, 206, 207, 215, 244, 245]. Its method of vapor transport has also been modeled. The configuration of the DVD system explored in this dissertation employed an electron beam gun to evaporate material in a low vacuum environment. An inert gas jet was then used to capture that vapor stream and transport it to a substrate for deposition. The system was created with the idea that it might be able to deposit a more focussed vapor stream onto flat and fibrous substrates with higher efficiencies and adatom energies than possible using existing thermal evaporation sources. In addition the system was initially envisioned as a highly flexible material synthesis tool for depositing material at varying adatom energies, angles, and distributions.

The two part model employed in this dissertation utilized the Direct Simulation Monte Carlo method developed by G. A. Bird to simulate the carrier gas flow directed at the sub-

strate and then employed fundamental bimolecular collision theory concepts to follow vapor atoms in the carrier gas flow from source to substrate. Vapor atoms were tracked through the system until they left the modeled volume or contacted the substrate. For atoms contacting the substrate, their velocity and position vectors were recorded. This information allowed adatom deposition efficiency, energy, angle, and distribution information to be tabulated for various processing conditions, providing additional material synthesis insight not available through the experimental work.

The experimental and modeling work of the dissertation showed that for certain specific applications the technology may represent a more attractive material synthesis pathway than existing vapor deposition techniques. DVD demonstrated an ability to create focussed efficient deposits onto selected substrate forms (e.g. fibers) where the gas scattering characteristics of the technology can be put to advantageous use, coating surfaces in and out of the line of sight of the vapor stream. The research of this dissertation also suggests DVD could prove useful in applications where elements from the gas phase need to be reacted and combined with elements which are normally liquids or solids at room temperature (e.g. thermal barrier coatings). Finally the modeling work of this dissertation suggests that there exists room for improvement of DVD technology through system reconfiguration and addition of other processing subsystems (e.g. substrate biasing or ion beam substrate modification tools).

13.1 Specific Conclusions

As a result of the work conducted for this dissertation, many specific conclusions can be drawn:

Experimental:

- A free jet expansion from a sharp-edged orifice does create a region of supersonic carrier gas flow inside the processing chamber.
- The carrier gas velocity (Mach number), deposition chamber pressure, and e-beam power are three of the most important processing parameters affecting the efficiency and distribution of deposited material in a DVD system.
- While Mach number, chamber pressure, and e-beam power are of primary importance, many other factors influence vapor deposition. Other important factors include vapor atom composition, carrier gas atom composition, length of source material rod and crucible temperature.
- For both flat substrate and fiber coating experiments, deposition efficiency initially rises, goes through a maximum and then decreases as the deposition chamber pressure increases.
- For both flat substrate and fiber coating experiments, the deposition efficiency increases with increasing Mach number at a fixed deposition chamber pressure (below the pressure at which peak efficiency is observed).
- For both flat substrate and fiber coating experiments, the deposition efficiency increases with decreasing Mach number at a fixed deposition chamber pressure (above the pressure at which peak efficiency is observed).
- For the experimental configurations examined, the position of the vapor source relative to the nozzle and substrate has some small effect upon deposition efficiency. Placing the crucible closer to the nozzle lip increases deposition efficiency.
- Under selected carrier gas velocity and chamber pressure conditions, Directed Vapor Deposition can deposit vapor onto fibers at twice the efficiency of traditional, high vacuum, line-of-sight vapor deposition systems.

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- The dependence of deposition upon a large number of process variables highlights the importance of incorporating sensors into the DVD system to monitor the critical issues of vapor source surface temperature, vapor composition and velocity, and film growth rate and surface temperature.
 - DVD can deposit compounds created via reaction between pure metals and gas phase elements.

Modeling:

- The DSMC plus BCT model developed in this dissertation can be used to model diode sputter deposition of materials. Compared to the theoretical predictions of other researchers reported in the literature, this model more accurately predicts energy loss between target and substrate resulting from vapor atom / background gas atom collisions.
- Vapor deposits created in the current DVD system are low energy deposits with a wide angular distribution of deposit.
- Variation of carrier gas flow Mach number and chamber pressure generates deposition efficiency trends which mirror those observed experimentally.
- While the current DVD system does not generally deposit vapor more efficiently than traditional e-beam systems for the same source to substrate distance, it can create deposits which are significantly more focussed than those systems under selected process conditions.
- The DVD system can be redesigned to provide vapor deposition efficiency above the level observed in the current DVD system and above the level achievable in conventional e-beam systems.

- To produce an accurate picture of vapor transport during Directed Vapor Deposition additional model development must be undertaken in which a flux of atoms is allowed to interact with the carrier gas stream. The single vapor atom approach employed in this dissertation allows accurate simulation of vapor transport only in the diffuse limit.
- Using the carrier gas stream to redirect the vapor atoms 90° toward the substrate is quite inefficient, wasting significant amounts of carrier gas and inefficiently depositing vapor onto a substrate. Much greater deposition efficiency can be achieved by using the carrier gas only to focus and accelerate the vapor stream.

13.2 Final Thought

As noted in the Introduction to this dissertation, the specific system examined for this research project might or might not become a desirable method for industrial application. However, by studying this method several application areas have been identified for the technology and better understanding of low vacuum materials synthesis has been generated. As Chapter 11 demonstrates, continued efforts to understand the system should lead to incremental improvements in the technology, ultimately resulting in the development of a well understood process technology with desirable characteristics for the synthesis of highly engineered materials in strategically selected applications.