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Commercial Aspects of Epitaxial Thin Film Growth in Outer Space

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ABSTRACT

A new concept for materials processing in space exploits the ultra vacuum component of space for thin film epitaxial growth. The unique low earth orbit space environment is expected to yield 10^{-14} torr or better pressures, semi-infinite pumping speeds and large ultra vacuum volume ($\sim 100 \text{ m}^3$) without walls. These space ultra vacuum properties promise major improvement in the quality, unique nature, and the throughput of epitaxially grown materials especially in the area of semiconductors for microelectronics use. For such thin film materials there is expected a very large value added from space ultra vacuum processing, and as a result the application of the epitaxial thin film growth technology to space could lead to major commercial efforts in space.

INTRODUCTION

The utilization of space for materials processing has been, in general, limited to the use of the micro-gravity aspects of space^[1,2]. Recently, however, studies have lead to the indication that another component of space, the vacuum component, can be significantly utilized for materials processing^[3,4], especially in the area of thin-film growth. Specific thin-film growth, described as epitaxial thin-film growth, has risen to importance recently due to the major promise of enhanced thin-film properties in new and unique materials systems^[5,6] and, therefore, commercial applicability of the technology. In this article, we describe both the benefits of the new thin-film epitaxial technology as well as the major benefits that the epitaxial growth technology can bring to the commercial development of space.

Epitaxial growth of thin-film materials has presently been exercised through mainly molecular beam epitaxy (MBE)^[7] or chemical beam epitaxy (CBE)^[8]. Epitaxy is the growth of thin crystalline films in which the substrate determines the crystallinity and orientation of the grown layer. This growth is accomplished in an atom-by-atom,

layer-by-layer manner. Molecular beam epitaxy is the growth of thin film materials by the reaction of one or more thermal molecular beams with a crystalline surface under ultra-high vacuum conditions. Chemical beam epitaxy is the reaction of one or more gaseous beams with a crystalline surface under high vacuum conditions. Note that in both instances, high vacuum is of prominence in the growth of high quality, defect-free, single crystal films.

The importance of high vacuum is clear in the MBE/CBE process. Of detriment to the growth of high purity, high quality thin films is contamination from the background vacuum environment, contamination from the beam sources themselves, and segregation of impurities from the bulk. The minimization of this contamination as well as minimization of interdiffusion and desorption within the film/substrate region will result in high quality, high purity thin-film growth. Such growth is currently attempted in rather sophisticated and large ultra-high vacuum systems which generally incorporate multiple-growth chambers, analysis chambers, and interconnecting ultra-high vacuum tubes within which samples are transported from one chamber to the other (Fig. 1). Such complexities are required for the practical growth of epitaxial thin films.

Applications of epitaxial films are many and can be broken down into areas of semiconducting materials and devices, metallic materials and devices, and superconducting materials and devices. In the semiconductor area, applications range from opto-electronics where lasers and detectors operating in the infrared region are of importance to communications and surveillance^[9], to millimeter wave sources and amplifiers operating in the 100 to 300 GHz range^[10], to high-speed digital logic and memory devices^[11]. Most all of these semiconductor devices and materials are based on compound semiconductors that have unique transport properties, but that cannot be readily generated in high quality, high purity form by earth-based MBE/CBE growth. In the metals arena, rare earth metal alloy thin films have applications in magneto-optic recording devices for high density magnetic storage of information^[12]. And finally, the new high temperature superconductors^[13] in epitaxial thin film form^[14] are expected to have applications across a wide spectrum of areas with micro-electronics seeing the first fruits of this new technology through, as example, superconductor interconnects in micro-circuits^[15].

An example of the epitaxial thin-film growth technology as applied to semiconductors is shown in Fig. 2. Note that in Fig. 2 the characteristic thickness of the grown layers of material is of the order of 20Å. This equates to approximately 15 to 20 atomic layers, and clearly shows the atomic resolution of the epitaxial growth technique which makes it so powerful for new and unique thin-film materials growth. The benefit of this MBE/CBE technology, therefore, is the precise fabrication of atomic scale perfect thin film structures with predetermined doping

and compositional profiles. In other words, this technology can be best described as micro-materials engineering. With MBE/CBE, we will be able to see the synthesis of artificial materials with prescribed characteristics. We will be able to see new and unique devices based on novel principles. We will be able to realize new sciences. Within the scientific community today, MBE/CBE has been described as the most powerful tool in the synthesis of new materials and the fabrication of novel micro-devices.

Current MBE/CBE Limitations

There are, however, limitations to application of the MBE/CBE technology.

1. High background doping and interface contamination; this is principally due to, a) the vacuum environment of the thin-film during growth — usually 10^{-8} to 10^{-10} torr, b) the purity of the sources of the materials that are being used for the growth process, and c) the "memory effect" of vacuum chamber walls that are constantly desorbing species to which they have been previously exposed.
2. Small throughputs; this is principally the result of limited chamber size. Most ultra-high vacuum chambers are of the order of 0.5 cubic meter volume, and as a result, can only have a limited number of samples processed by the epitaxial growth technique. In addition, because of the complexity and sophistication of the equipment utilized for the growth process (Fig. 1), there is a significant amount of downtime in most all of the machines that are currently in use.
3. Sample non-uniformity; because of the limited chamber size, the source to sample distance remains relatively small (of the order of 20 centimeters). Under these conditions, the source output is not spatially uniform, and as a result, substrates must be rotated during exposure to the source beams. Such rotation improves uniformity of the grown layers, however, larger source to sample distances would further improve the uniformity of the grown films.
4. Chamber wall contamination; in the current technology, a finite size chamber is used for the growth process. During growth, the chamber walls are also generally coated with the growing material due to overspray. Such coatings on the walls later plague future thin film growths since these coatings are continually desorbing into the vacuum chamber. This contaminates the vacuum environment, and as a result contaminates the grown layers. Therefore, a vacuum chamber used for the growth of one material cannot be readily used for the growth of another. This, consequently, restricts the use of a given chamber (representing a significant amount of capital cost — ~\$1 Million), to a one-material, one-machine status.

Such a situation does not make MBE/CBE suitable for the empirical approach that has shown in the past in the past to be so productive in a generation of new materials and devices.

5. Toxicity of gases used; within the chemical beam epitaxy technique, the gases that are used are generally toxic, and as a result, have to be removed from the vacuum chambers within which they are used. This generally involves rather elaborate and quite expensive, pumping, scrubbing and cleaning techniques for the gases.

Space Benefits for MBE/CBE

Vacuum in space offers the possibility of alleviating the noted earth-bound limitations on the MBE/CBE technology. Space ultra vacuum has the following advantages:

1. An ultra-high vacuum of the order of 10^{-14} Torr hydrogen with 10^{-18} Torr or lower pressures for other gases.
2. Semi-infinite pumping speed.
3. Large vacuum volume without walls.
4. Processing capabilities as a result of solar bakeout, atomic oxygen, atomic hydrogen, micro-gravity, and 3°K background radiation.

These space ultra vacuum benefits can, however, only be realized through the utilization of space flight equipment currently defined as the space ultra vacuum research facility (SURF)[16]. The space ultra vacuum concept was first described nearly fifteen years ago[17,18] with, however, little identification of needs for ultra vacuum. The current scientific and commercial interests in epitaxial growth have refocused interest in the utilization of the ultra vacuum of space for thin-film epitaxial growth.

Space Ultra Vacuum

The vacuum environment at the low earth orbit (300 Kilometers) is between 10^{-7} to 10^{-8} Torr and is mostly atomic oxygen. This is a relatively poor environment for epitaxial thin-film growth processes, however, it can be drastically improved by flying a shield behind which an ultra vacuum region is created.

A proposal for such a shield vehicle, made early on in space vacuum studies[3,19] and recently refined, is that of a circular shield in orbit, behind which the ultra vacuum experiments can be undertaken. Calculations indicate that

behind such of shield gas pressures would be on the order of 10^{-14} Torr for hydrogen, 10^{-18} for oxygen, and lower for other species. This basic concept for space ultra vacuum, the wake shield, is shown in Fig. 3.

Thin Film Epitaxial Growth in Space Ultra Vacuum

Materials that are being considered for epitaxial growth within the space ultra vacuum include semiconductors, metals, and superconductors. In the semiconductor area, III-V materials — principally gallium arsenide/gallium aluminum arsenide, are gaining importance due to their infra-red behavior for lasers and detectors and due to their high electron-mobilities that can result in high-speed transistors. Terrestrial materials still have relatively high defect levels ($\sim 10^{14}/\text{cm}^3$) and hence, require improvements which we feel space ultra vacuum can offer^[7]. The cost of the "improved" material is the cost of adding 1000 or so high, quality, high purity atomic layers to a GaAs substrate. The amount of weight added is small, but the improvement in the quality and usefulness of the resultant wafer could be phenomenal. The small weight added through the result of the addition of the near perfect thin film layer would be accompanied by an increase in value of the material that could surpass many orders of magnitude. This large value added makes for ideal commercialization possibilities in the utilization of the space ultra vacuum.

In terms of the commercial impact of thin film epitaxial growth, we will first address three possibilities for the enhancement of the current state of technology in three general areas and then look at the possible economic impact of the advancement of the state of thin film technology. Gallium arsenide and gallium aluminum arsenide were previously mentioned as a semiconductor of interest for high-speed transistors. All of our current computational technology is based on silicon. If gallium arsenide microcircuits were available, one could realize a factor from 50-100 times faster computation with a factor of 10 times lower power consumption for gallium arsenide than for silicon based microelectronics. Space ultra vacuum could allow for the realization of such a possibility through space production of high quality gallium arsenide, and thereby, open up a major market for materials produced in space.

A second possibility for commercial impact of space ultra vacuum is the before-mentioned magneto-optic recording based on rare earth alloy superlattices. Magneto-optic magnetic recording has its roots in the Kerr effect which relates the change in polarization of incoming optical radiation to the magnetization of the recording medium. Within this technology, there is no head-medium interaction, as is currently the case in magnetic recording. In addition, it is expected that there would be a factor of $\sim 10,000$ increase in bit density with magneto-optic recording as compared to present magnetic recording. Such an enhancement would be expected to significantly further

information storage technology. Thin film rare earth alloy materials show high performance in magneto-optic recording, and as a result, would be ideal for utilization in this technology. Rare earth alloy thin films, however, are plagued by oxygen contamination. Such contamination can be removed or totally eliminated in the space ultra vacuum environment, therefore, space ultra vacuum processing of thin films for magneto-optic recording is a viable possibility for future development.

We also have the possibility of growing in space integrated thin film semiconductor and thin film superconductor materials and devices. It is well to note that in moving from metallic interconnects to superconducting interconnects in microelectronic circuits, one could realize lower capacitive coupling, and hence, increased response time for these systems. Again, a major benefit for microelectronics technology. As noted, the space environment shows major benefit for thin film superconductor growth, and we have also already identified benefits for thin film semiconductor growth, therefore, the integration of these two technologies in the space ultra vacuum is a unique application of the space environment for materials processing.

In turning to the economic impact of thin film epitaxial growth in space, one needs mainly to identify the fact that at the present time, the semiconductor device industry is approximately \$35 billion/year. (With the prediction that nearly \$9 billion/year will be spent on gallium arsenide devices by 1990.) The magnetic information storage industry is an additional approximately \$15 billion/year, and there is yet no reliable prognostication of what the thin film superconductor industry will be in five to ten years. We see, therefore, that nearly \$50 billion/year is currently being spent in commercial areas where we have identified thin-film epitaxial growth in space as making a significant impact. The ultra vacuum component of space, the infinite pumping speeds, the large working volume and the expected high throughputs, all indicate that by the 1990's, an expectation of a 1% impact on the industry would not be unreasonable. That conservative 1% impact translates into the hundreds of millions of dollars per year of commercial use of space vacuum, and as a result, such use will be a strong foothold for materials processing in space and for future commercial development of space.

Summary

As we have noted, although MBE/CBE is principally a laboratory tool at this point in time, it has already shown the promise of growth of new and advanced materials and devices. The space ultra vacuum environment will allow exploitation of the full potential of the MBE/CBE technology both in the research arena and in commercial

areas. We expect the utilization of space ultra vacuum for epitaxial growth to result in the fabrication of new and near-perfect materials and devices which will find commercial markets both on earth and in space. This commercialization possibility will be aided by the large value added expected for the epitaxial thin film growth, and it is believed that the first space-grown thin-film will be used in the microelectronics area.

Acknowledgement

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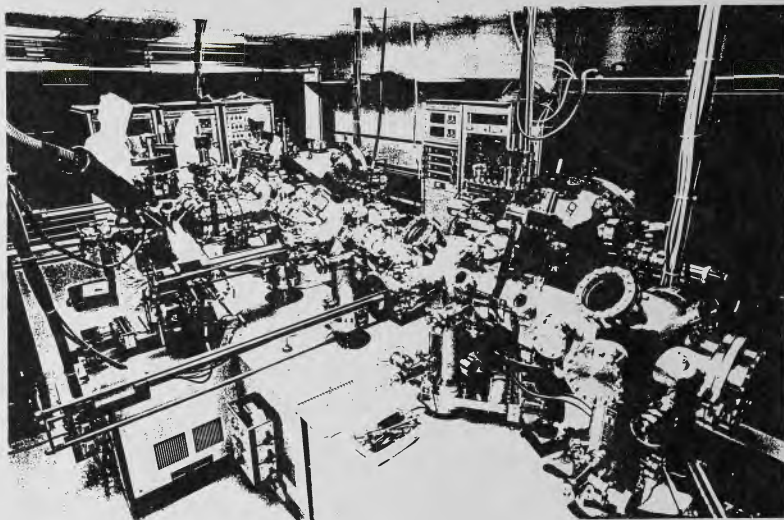


Fig. 1.

Two Epitaxial growth chambers with interconnecting vacuum stations and analysis chambers located at the Space Vacuum Epitaxy Center.

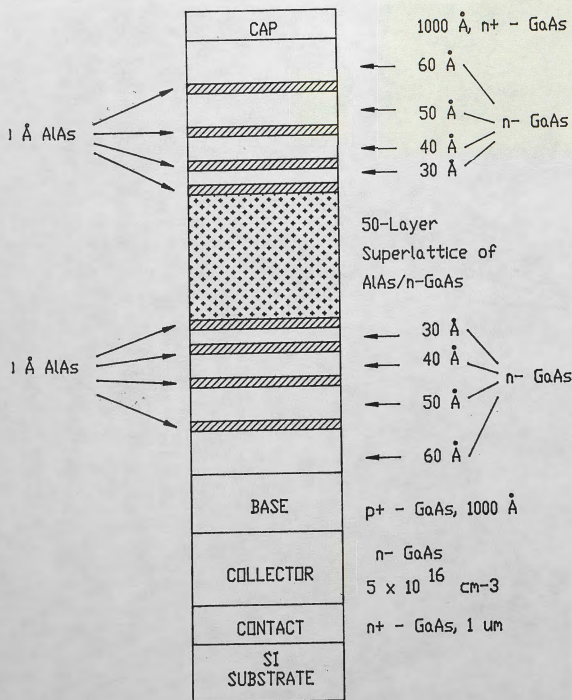


Fig. 2.

Schematic of an MBE grown material: a GaAs/AlAs superlattice bipolar transistor. Note the characteristic layer thickness of 20 Å (approximately 20 atomic layers).

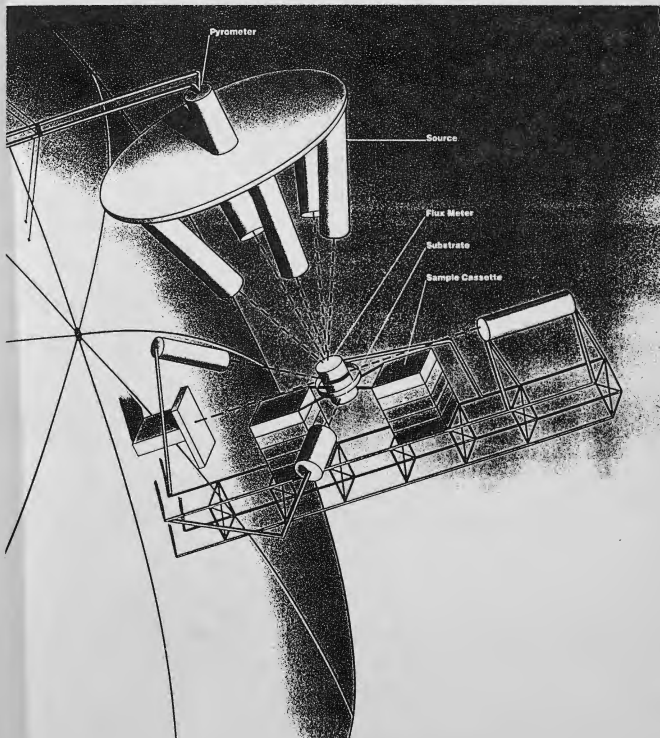


Fig. 3.

Operation of the wake shield with MBE/CBE system on the shuttle remote arm.

- (1) Deployment from Payload Bay.
- (2) Clean up by atomic oxygen-shield oriented with experiment package pointing in ram direction.
- (3) Further cleaning by solar bake out — shield turned toward sun.
- (4) Thin film epitaxial growth — experiment package pointed opposite ram direction.

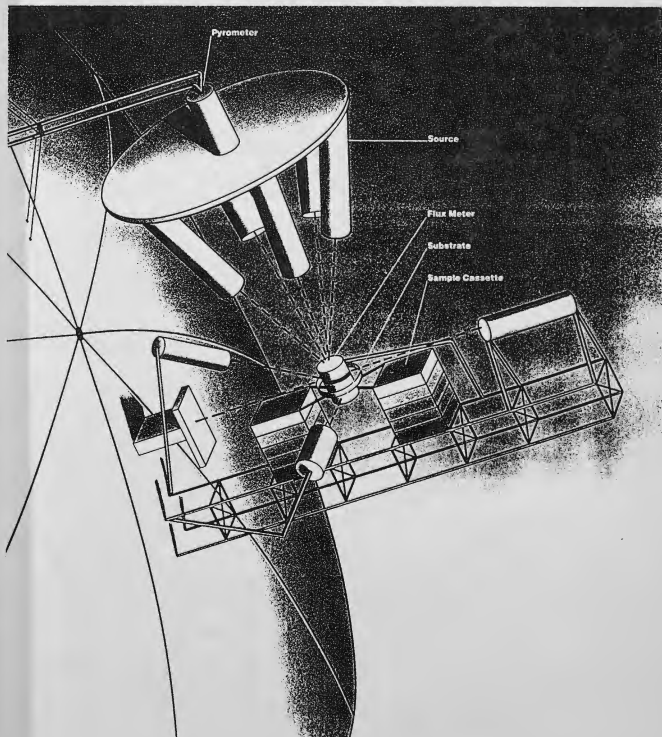


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