PRODUCING GALLIUM ARSENIDE CRYSTALS IN SPACE

by

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ABSTRACT

The production of high quality crystals in space is a promising near-term application of microgravity processing. Gallium Arsenide is the selected material for initial commercial production because of its inherent superior electronic properties, wide range of market applications and broad base of on-going device development effort. Plausible product prices can absorb the high cost of space transportation for the initial flights provided by the Space Transportation System. The next step for bulk crystal growth, beyond the STS, will come later with the use of free flyers or a space station, where real benefits are foreseen. The use of these vehicles, together with refinement and increasing automation of space-based crystal growth "factories," will bring down costs and will support growing demands for high quality GaAs and other specialty electronic and electro-optical crystals grown in space.

INTRODUCTION

As the demand grows for faster and larger integrated circuits, interest is intensifying in electronic materials which offer promise of surpassing the limits of silicon based semiconductor technology. Gallium arsenide (GaAs), is generating particular interest because of its inherent advantages in terms of high switching speeds, low power dissipation, temperature tolerance and radiation resistance. Also, GaAs has the advantage that it emits coherent light.

These advantages will continue to stimulate GaAs device development in the years ahead. Increasing application of GaAs semiconductor technology is to be expected in support of increasing performance demands for high speed signal and data processing, radiation hardened military systems, phased array radars, satellite communication, mainframe computers, fiber optic communications, VHSIC and VLSIC.

GROUND-BASED METHODS OF CRYSTAL GROWTH

Commercial crystal growth is accomplished by two processes, bulk and epitaxial.

Bulk crystal growth methods can produce very large crystals, 200 pounds or more, but the process utilizes large, heavy furnaces, high temperatures (1250°C), high power (up to 300 KW) and high pressures (up to 150 atmospheres). Further, the crystals produced are plagued by imperfections and impurities. The crystal properties vary by over an order of magnitude per inch radially, axially and azimuthally, and even so-called high-grade crystals contain 10^{15} impurities and 10^5 vacancy sites per cubic centimeter. These imperfections degrade the electrical performance, reliability and useful life of electronic and electro-optical devices.

Epitaxial crystal growth avoids many of the problems of bulk processing. Here the crsytal material is deposited layer upon layer on a crystal seed. The process achieves more uniform crystal structure but is very slow and produces only thin layers of small diameter (½ inch) crystals. Typically, epitaxial crystals have been layered upon slices of bulk crystal to fabricate devices, and is not compatible with growth of bulk quantities.

Improvements in crystal growth technique for both bulk and epitaxial processes have proven very difficult to achieve. Even with silicon, a relatively simple material, improvements are still being sought after 30 years of development. The major barriers in bulk growth are in improving crystal uniformity and purity and in reducing defect density. The barriers for epitaxial growth are in scaling to larger sizes and increasing growth rate.

The primary difficulty in surmounting these barriers lies in the fact that all growth techniques involve phase transformations from liquid to solid state and therefore involve density and temperature gradients. These gradients are the source of several different complex flow processes which cause spatial and temporal fluctuations in the growth of the crystal. Particularly significant are gravity driven convection currents which create disturbances that are particularly troublesome at the crystal growth interface.

Many efforts have been made to suppress gravity driven convection currents, with only limited success. One method, developed at MIT, applies a strong magnetic field across the molten material to suppress the currents. This results in some slowing of convective flow by simulating an increase in the viscosity of the melt, but produces only p-type material. N-type or semi-insulating material has not been successfully produced by this method. Another technique employs very steep thermal gradients at the crystal growth interface. This approach has been effective in reducing stoichiometric oscillations and constitutional supercooling, but it cannot be scaled up in a gravitational environment without causing convection. Other methods are being tried and improvements are expected. However, because of the fundamental role played by gravity in fluid dynamics, improvements of Earth-based crystal growth processes are expected to be limited in scope, and concentrated mainly in structural improvements as opposed to compositional. In space, on the other hand, where the effects of gravity are all but eliminated there is promise that bulk quantities of epitaxial quality crystals can be successfully grown.

LIQUID PHASE ELECTROEPITAXIAL CRYSTAL GROWTH

The electroepitaxial method of crystal growth makes use of an electric current passed through the molten solution and the seed to force migration of the solute to the liquid-solid interface where growth occurs in epitaxial layers. Supersaturation takes place in the immediate vicinity of the growth interface and growth is controlled by the rate of transfer of solute, under the electric field, to the interface. This method appears particularly attractive for the processing in space of III-V crystals, such as GaAs and InP.

A major advantage is that crystals can be grown by this process far below the melting point of the compound. In the case of GaAs, crystals have been grown electroepitaxially at temperatures ranging from 800°C to 950°C. The lower temperature allows operation below the compositional instability region and reduces dissolved impurities. Also, the problem of arsenic vapor pressure is essentially eliminated.

Further, the electric current allows control of growth rate and of doping concentration. Attainable growth rates under this process are adequate to support bulk production for commercial purposes. The electroepitaxial method, in the microgravity environment, permits the controlled growth of ternary and quarternary crystals.

THE MARKET FOR GaAs

Interest in GaAs as a desirable semiconductor material has existed over many years. As compared to Si, GaAs offers switching speeds up to 10 times faster, power consumption of only 3 to 4 percent, higher and lower temperature tolerance, higher radiation resistance - and it emits coherent light. The poor quality of available material, however, discouraged GaAs device development effort until recently. Only in the past several years have better GaAs crystals become available from improved processing techniques. As a result, development activities aimed at marketable GaAs devices have accelerated rapidly. Some market analysts are now forecasting that world-wide sales of GaAs integrated circuits will exceed 3 billion dollars by 1995 and approach 140 billion dollars by the year 2000. Important applications of GaAs devices are foreseen in support of advanced communications systems, high speed data processing, artificial intelligence, smart weapons and micro-wave signal processing, among others, where the special speed, power, temperature tolerance, radiation resistance and light emiting characteristics of the material will prove significant.

Space produced GaAs will cost a great deal more than that produced on Earth, primarily because of the very high cost of space transportation. Applications for this special material are expected to be limited to devices requiring the utmost in electronic performance, reliability and lifetime, and where the cost of the material will represent only a minor portion of that of the finished system. These conditions will be present in such rapidly evolving areas as satellite communications, defense communications, mainline computers, artificial intelligence, high powered lasers, wafer scale integrated circuits and various smart weapons and defense systems.

Although market demands for new materials are always difficult to predict, it is estimated that by 1990 requirements for space grown GaAs will be in the order of 30 to 50 kg. With expanding applications thereafter, and with other types of crystals being introduced to space processing. MRA expects the market to grow substantially thereafter.

ENHANCEMENT OF CRYSTAL GROWTH BY SPACE PROCESSING

Semiconductor single crystals constitute the basic framework of solid state electronics, and their quality (chemical and structural) has been, and will continue to be, the rate determining factor in semiconductor device and system advances. Improvements in device characteristics over the years (in terms of speed, power, sensitivity, etc.) have stemmed directly from improvements of single crystal characteristics. Often, new device and system concepts have had to await needed advancements in single crystal quality and/or dimensions. The significance of crystal quality improvements made possible by space processing should be viewed in this light.

Fortunately, crystal growth experiments in space have already demonstrated the marked improvement which can be achieved by growing the crystals in a microgravity environment. Also, improved capabilities for characterizing crystals and a better understanding of the art and science of crystal growth stemming from serious laboratory research in recent years, make possible a better evaluation of the quality enhancement achievable in space as well as the expected limits of Earth processing methods.

Since no crystals have yet been grown in space using the electroepitaxial method, actual measurements of the quality attainable must await the early experiments of the MRA joint endeavor. Ground based laboratory experiments, along with analysis of results of prior experiments in space using other growth techniques, do suggest that the quality of crystals grown electroepitaxially in space will be substantially enhanced over those grown on Earth.

Particularly, it is expected that the experiments of the joint endeavor will demonstrate that bulk crystals produced electroepitaxially in space, as opposed to Earth grown crystals, will be compositionally and structurally homogeneous, striations eliminated, and the concentration of impurities and defects (of all types) greatly reduced.

Since inhomogeneities, impurities and other defects degrade electronic performance of the crystal and lead to earlier breakdown, the availability of high quality crystals from space production can lead to important advances in device performance, reliability and useful life.

THE NASA/MRA JOINT ENDEAVOR

NASA and Microgravity Research Associates (MRA) entered their joint endeavor agreement in April 1983. The endeavor is to develop the electroepitaxial method for growing semiconductor crystals in space. GaAs is identified as the crystal material of choice for this endeavor.

The terms of the agreement specify that MRA will be responsible for developing the experiment to be flown and for providing the necessary growth furnaces and support equipment for conducting the experiments. Also, MRA is committed to commercialize the product after the completion of joint endeavor. NASA is responsible for providing seven flight opportunities without charge and for furnishing integration services. There is provision for an eighth flight if it is mutually agreed that it is needed. No exchange of funds is involved, but NASA has access to the science resulting from the endeavor and will receive some quantities of the crystal materials produced in space. Over the series of seven flight missions, the electroepitaxial process will be verified and refined and the furnace equipment will be tested, scaled up, improved and readied for post-endeavor commercial crystal growth operations in space.

The last several flight missions of the endeavor (in the 1987-1989 time period) will produce quantities of space grown crystals sufficient for wide-scale distribution to electronic materials laboratories for their evaluation, as well as to support initial sales to users of semiconductor crystal materials.

SPACE TRANSPORATION SYSTEMS

The Space Shuttle is well suited to support the research and development phases of the MRA program for producing bulk quantities of high quality GaAs crystals in space. All essential services, including electrical power, heat dissipation, and provision for monitoring and control systems, are present. These services will support the growth of 15, and possibly up to 20 kilograms of GaAs crystal on flights which do not need to accomodate other significant users of electrical power. These production quantities will be sufficient for initial commercial production. As market requirements expand, however, the limited power available on the Shuttle and the relatively short duration of Shuttle missions will not be adequate to support needed production increases. By the early 1990s MRA must be looking to other space vehicles such as free flyers or a space station to accomodate its requirements for growing bulk quantities of crystals for the market. These vehicles will have greater amounts of electrical power available, and the growth process can continue over longer periods of time.

The cost of space transportation is also a major consideration. Missions aboard the Space Shuttle, where furnaces and support equipment must be carried up and down, are very expensive and will require that the finished crystal product be marketed at a price much above that of crystals produced on Earth. The cost of production aboard Shuttle-serviced free flyers or a space station, where the furnaces will remain in orbit, are expected to be considerably less. This saving can reflect in lower market price which, in turn, will stimulate market demand. However, it should be noted that regardless of which mode is used, Shuttle sortie, or Shuttle-serviced free flyer or space station, transportation costs using the Shuttle Transportation System are the dominant part of production costs. These costs, unless significantly reduced, will keep the price of space products restrictively high.