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METAL NITRIDE SEMICONDUCTORS FOR OPTICAL APPLICATIONS

The structural and electronic properties of wide-bandgap semiconductors consisting of aluminum, gallium, and indium nitrides and their alloys make them excellent candidates for use in constructing solid-state optical devices operating from the visible to the ultraviolet. Fabrication of these materials is being approached from two perspectives: reactive magnetron sputtering and metal-organic chemical vapor deposition. Successful synthesis of these metal nitrides will ultimately lead to simple (light-emitting diode) and complex (laser) sources, nonlinear optical elements, and semiconductor detectors, all matched to the wavelength of the spectral region of interest.

INTRODUCTION

Solid-state electronic devices that function as sources and detectors of light have made possible products ranging from simple light-emitting diodes, common in everyday life, to more complex systems, such as the compact-disk player and optical mass storage media for computers. Such devices depend on the production of extremely pure, highly crystalline semiconductor materials and the reproducible formation of either *p–n* or metal–semiconductor junctions.

Historically, semiconductor science has progressed from the study of elemental solids such as silicon and germanium to the study of compound materials such as gallium arsenide (GaAs) and cadmium telluride (CdTe). The progress resulted from the need for devices that can operate at higher speeds and for materials that display divergent bandgap properties. The higher operating speed of GaAs-based structures has resulted in solid-state devices that operate at microwave frequencies, and the larger bandgap materials, such as CdTe, have led to the development of semiconductor optical devices that operate throughout the visible region of the electromagnetic spectrum.

Recent advances in tailoring the physical properties of bulk semiconductors have been matched by deposition technologies that allow the growth of nearly single-crystalline thin films with film thickness controlled to atomic dimensions. The techniques—molecular-beam epitaxy and metal-organic chemical vapor deposition—require ultraclean conditions and depend on a slow, layer-by-layer growth of material at high temperature (1273 K) to promote epitaxy. Such epitaxial film structures form the basis of semiconductor superlattices—atomically thin alternating layers of different materials. The prototypical system in these studies is the gallium aluminum arsenide ($Ga_xAl_{1-x}As$) alloy, which has been widely investigated because high-quality GaAs and AlAs are available and the crystal-lattice parameters of the two are very nearly identical. Much interesting science, such as the integral and fractional quantum Hall effects, and important technology, such as quantum-well devices, multiple-quantum-well lasers, and high-electron-mobility transistors, have been developed using these materials and techniques. The only limitation of the $Ga_xAl_{1-x}As$ system is that the relatively small bandgaps of GaAs (1.35 eV) and AlAs (2.16 eV) restrict optical sources based on these materials to the red and near infrared regions of the spectrum. Because of that limitation, interest in materials having larger bandgaps has been renewed.

APPROACH

We have begun studies on a class of wide-bandgap semiconductors that hold great promise for use as light sources, detectors, and nonlinear optical elements covering the visible and extending into the ultraviolet regions of the electromagnetic spectrum. Members of this class of compounds include aluminum nitride (AlN), gallium nitride (GaN), and indium nitride (InN). All are isomorphous (of the same structure), crystallizing as hexagonal phases characteristic of wurtzite[1] (Fig. 1). Moreover, they all exhibit a direct bandgap,[2,3] a necessary criterion for high-efficiency semiconductor optical devices. Lattice parameters, bandgaps, and the wavelengths of light equivalent to the bandgaps are listed in Table 1.

Table 1—Semiconductor parameters of aluminum, gallium, and indium nitrides.

	Lattice parameters (Å)		*Bandgap*	*Wavelength*
	a	*c*	*(eV)*	*(nm)*
AlN	3.111	4.978	6	200 (UV)
GaN	3.186	5.178	3	400 (near UV)
InN	3.541	5.705	2	600 (red)

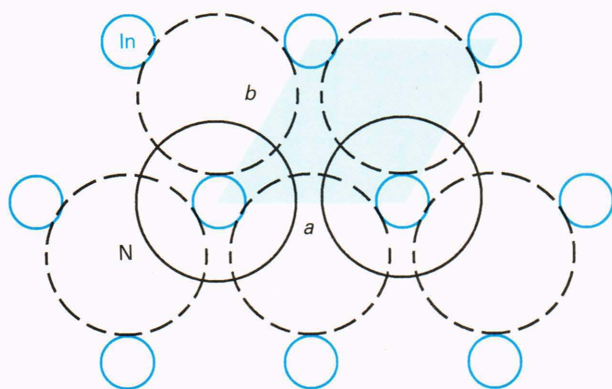


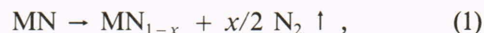
Figure 1—View down the *c* axis of the wurtzite crystal structure of indium nitride. Nitrogen atoms at $-c/8$ are dashed; those at $3c/8$ are solid. The indium atoms lie at $c = 0$. The formally In^{3+} and N^{3-} ions exhibit fourfold (essentially tetrahedral) coordination.

As the table indicates, the bandgaps of these three compounds range from 2 to 6 eV, corresponding to emitted (or detected) light of wavelength from 600 (red) to 200 nm (ultraviolet), a very important spectral region for consumer and military optical devices. Note in Table 1 that the variation in lattice constant between members of the series is fairly small. One ramification of the small variation is that alloys can be formed throughout the entire compositional range.[4,5] Moreover, the similarity of the *a*-axis lattice constants makes feasible the formation of semiconductor superlattices with *c*-axis texture.

In addition to the intriguing possibility of constructing optical sources and detectors that can operate at any wavelength throughout the visible and ultraviolet portion of the spectrum, metal nitrides can also form the basis for nonlinear optical elements. As previously mentioned, these materials crystallize in a wurtzite structure with point group symmetry *6mm*. Such crystals belong to a class of noncentrosymmetric materials that have nonzero values for both the even and the odd terms of the higher-order optical susceptibility.[6] Consequently, these substances are capable of exhibiting nonlinear effects such as optical second-harmonic generation and bistability. In fact, preliminary work on AlN[6,7] and GaN[8] demonstrated second-harmonic generation in films of both materials, with values for the coefficients of the nonlinear optical susceptibility that compare favorably with other wide-bandgap semiconductors such as cadmium sulfide (CdS), zinc sulfide (ZnS), cadmium selenide (CdSe), and silicon carbide (SiC). These results, coupled with the excellent thermal properties of the metal nitrides, make AlN and GaN outstanding candidates for nonlinear optical materials for short-wavelength, high-power applications.

Although the situation outlined so far is optimistic, significant problems with these materials make investigating them particularly challenging. The emphasis placed on these and other compound semiconductors by semiconductor science and engineering has led to new problems in the production of device-quality material. The most important of which is nonstoichiometry, a deviation from the ideal chemical composition of the compound. For the elemental semiconductors, such as silicon and germanium, the technical problems centered on removing all trace impurities. Once those problems were solved, a single crystal of the purified material was then of device quality and could be doped *p*-type or *n*-type, as necessary. For compound semiconductors, the problems are magnified: not only do the constituents have to be exceedingly pure, but the material must also be stoichiometric. The stoichiometry for GaAs can be defined as the state of the system in which the ratio of the number of gallium atoms to the number of arsenic atoms is exactly one. Slight deviation from this state leads to material that is practically unusable. Over the last 20 years, considerable effort has gone into solving the problem of nonideal compound formation in GaAs[9], and it is now possible to form device-quality GaAs by a variety of techniques.

The situation now with metal nitride semiconductors is analogous to that in the early years of GaAs technology. Significant technical obstacles must be overcome before use of such materials becomes practical. The main concern now is the propensity of the materials to decompose chemically at moderately high temperatures, according to the reaction



$$MN \rightarrow MN_{1-x} + x/2\ N_2 \uparrow \ , \qquad (1)$$

where M = Al, Ga, or In. It is essentially such resulting small deviations from stoichiometry that are at the focus of our research on metal nitride semiconductors, much as comparable deviations led earler researchers to develop techniques for producing stoichiometric GaAs.

Although all compound materials will decompose if temperatures are high enough, the metal nitrides follow a thermodynamic path that causes them to decompose before they reach the melting point.[10] As a result, it is practically impossible to grow a single crystal of a stoichiometric metal nitride semiconductor by typical solution or melt techniques. Experimenters have therefore turned to a variety of nonequilibrium techniques, such as vapor-phase epitaxy, liquid-phase epitaxy, and molecular-beam epitaxy in an attempt to grow high-purity metal nitrides. These techniques, although an improvement, still produce materials with high free-carrier concentrations ($>10^{18}$ cm^{-3}) and low carrier mobilities (at best 200 cm^{2}V^{-1}s^{-1}), characteristic of defect-ridden, nonstoichiometric compounds. The high-temperature processing demanded for growing epitaxial films[11] causes decomposition according to Eq. 1.

The focus of our research is to explore lower-temperature processes that should allow the formation of materials having a minimum defect density while retaining the epitaxial nature of the films that is so important for constructing devices. We have chosen to pursue two parallel paths toward developing high-quality materials: metal-organic chemical vapor deposition and radio-frequency reactive magnetron sputtering. We will describe the two techniques in detail and discuss the preliminary results obtained with materials that have been produced.

We use a common complement of test and analysis equipment to ascertain the quality of the semiconductors produced. Included are a variety of optical, electrical, magnetic, and structural analysis tools. Figure 2 shows the techniques commonly used for characterizing materials.

RADIO-FREQUENCY REACTIVE MAGNETRON SPUTTERING

The radio-frequency reactive magnetron sputtering (RFRMS) technique employs RF excitation at 13.56 MHz, a magnetron sputtering source, and a chemically reactive gas to deposit thin films of compound materials. Sputtering in general has long been used for the deposition of a wide variety of substances such as metals, alloys, and dielectrics, but infrequently used to produce device-grade semiconductors, since other techniques generally produce higher-quality films of typical semiconductors. We believe, however, that RFRMS, described shortly, has considerable potential for producing high-quality metal nitride semiconductors.

The basis of the sputtering process[12] is the production of a plasma by RF or DC excitation in a rarified atmosphere typically consisting of an inert gas (commonly argon, Ar) with perhaps a small amount of reactive gas (typically nitrogen or oxygen) added. The energetic ions of the plasma are confined by means of a strong magnetic field and are accelerated toward a target material (electrically conducting substances for DC sputtering; either conductors or insulators for RF sputtering). When the ions strike the target, some of the material is ejected onto a substrate located nearby. The result is the deposition of a thin film of the target material if only an inert gas is used or in a thin film of a compound if a reactive gas is present in the sputtering chamber.

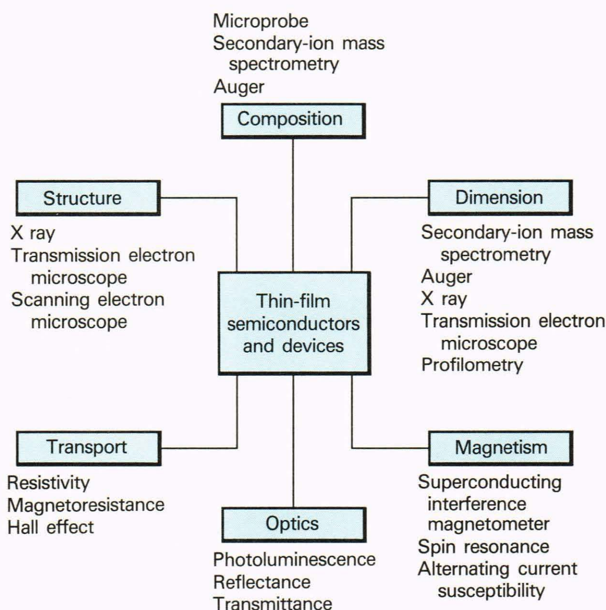


Figure 2—Typical battery of physical probes applied to thin-film semiconductors and devices.

The magnetron sputtering system used at APL is built on a liquid-nitrogen-trapped, diffusion-pumped vacuum station having base pressures on the order of 3 μPa. Figure 3 shows a block diagram and photograph of the system. It features dual magnetron sputtering sources mounted below a rotatable substrate platform. Magnetron sputtering guns were chosen for their small size and high sputtering rates. Directly above the sputtering guns are shutters that allow one or both guns to be blanked off during the sputtering operation. The substrate platform was designed to rotate so that superlattice films can be deposited by moving the substrates over the two different guns in a predefined sequence. The substrates can be heated by back illumination using a quartz lamp. The temperature is monitored by a thermocouple; the thermocouple output is fed to a microprocessor-based temperature controller to vary the temperature in a manner defined by the user. A variety of pressure-measuring instruments are incorporated into the system, including a capacitance manometer for high-accuracy measurement in the pressure range used for sputtering. The amounts of inert (Ar) and reactive (N_2) gases are controlled by a partial-pressure analyzer and controller, based on a quadrupole mass spectrometer.

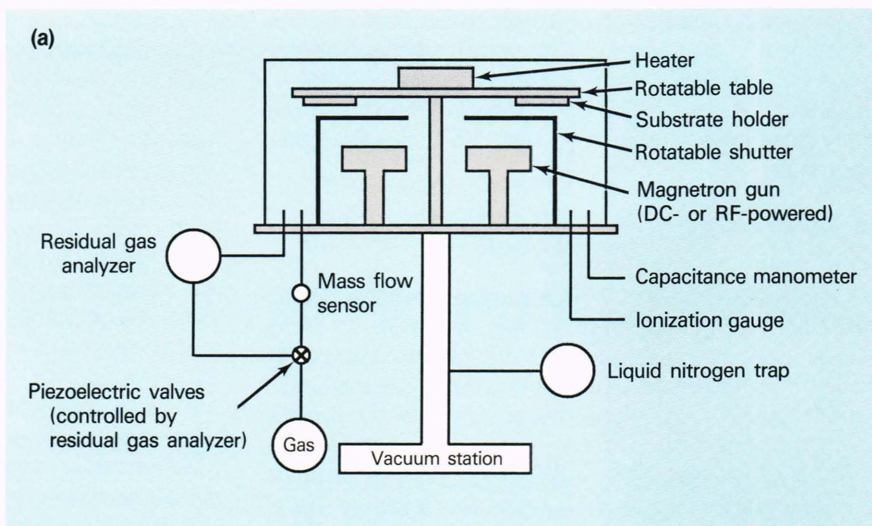
The targets used to produce the metal nitride semiconductors are high-purity metals—Al and In—and the nitrides—AlN, GaN, and InN. When the metal targets are used, the reaction during deposition is

$$M + N_2(\text{excess}) \rightarrow MN_{1-x} \ . \qquad (2)$$

The nitrogen content of the material, and thus its physical properties, can be controlled by varying the amount of N_2 gas in the sputtering chamber. We outline here a series of experiments conducted on AlN and InN to illustrate the control over the properties of the semiconductors by this process.

The sputtering target used for the AlN studies was 99.999% pure aluminum metal, the substrates were randomly oriented single-crystal sapphire, and the various N_2 concentrations used ranged from 50 to 5%. When the N_2 concentration was high, the material was highly resistive ($\sim 10^{12} \Omega$ cm), nearly clear, and had an optical absorption spectrum (Fig. 4) typical of a semiconductor with a bandgap of 6 eV. When the N_2 concentration was low ($<12\%$), the deposited AlN was of much lower resistivity ($\sim 10^{-2} \Omega$ cm) and was highly absorbing (black). The resistivity behavior of deposited AlN as a function of nitrogen content in the sputtering chamber is shown in Fig. 5, where it is evident that the material undergoes a sharp metal-to-insulator transition, and the resistivity changes by 10 orders of magnitude. Thus, by varying the amount of nitrogen in the system, the electrical resistivity at room temperature can be varied by more than 10 orders of magnitude (from that of one of the best insulators known to that of a metallic conductor).

Obtaining the electrical transport properties of the insulating AlN materials is problematic because of two ma-



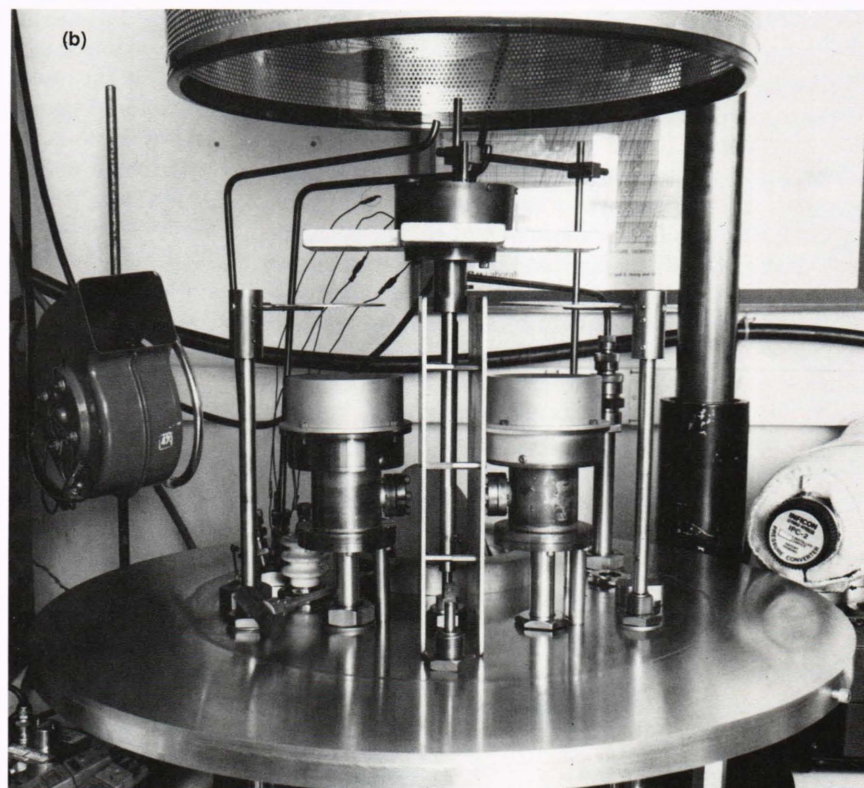


Figure 3—The magnetron sputtering system: (a) schematic diagram; (b) photograph.

jor experimental complexities: the first is the difficulty of obtaining reliable ohmic contacts between metals and wide-bandgap semiconductors,[13] and the second arises from the general electronic difficulties associated with measuring extremely high resistances.[14] The contact problem was solved by fabricating graded contacts. After the deposition of an insulating film, the procedure is to position the substrate so that a mask can be placed in front of it. The substrate and mask are then moved back to the sputtering location, and a graded contact is sputtered onto it. The graded contact is formed by first sputtering a layer of AlN that is compositionally equivalent to the underlying layer. The Ar/N_2 ratio is then slowly and continuously decreased until a contact is built up that varies from insulating AlN to metallic aluminum. To prevent the formation of a surface oxide layer, all the manipulations are performed without breaking the vacuum.

A high-impedance Dewar insert for measuring the temperature-dependent resistance of the required insulating metal nitrides has been designed and constructed at APL. The system is based on a digital electrometer having a high input impedance (10^{14} Ω), a constant-current source capable of reproducible subpicoampere outputs, and a custom sapphire sample holder. As is standard in measurements of high impedance, the electrical leads

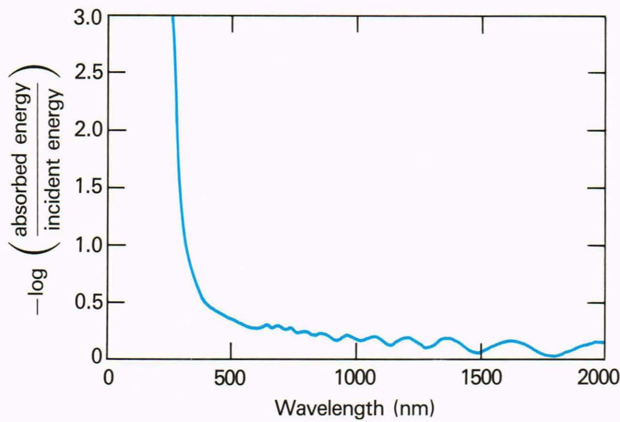


Figure 4—Absorption spectrum of a sputtered thin film of AlN. The interference pattern at long wavelengths is characteristic of the thickness and refractive index of the films.

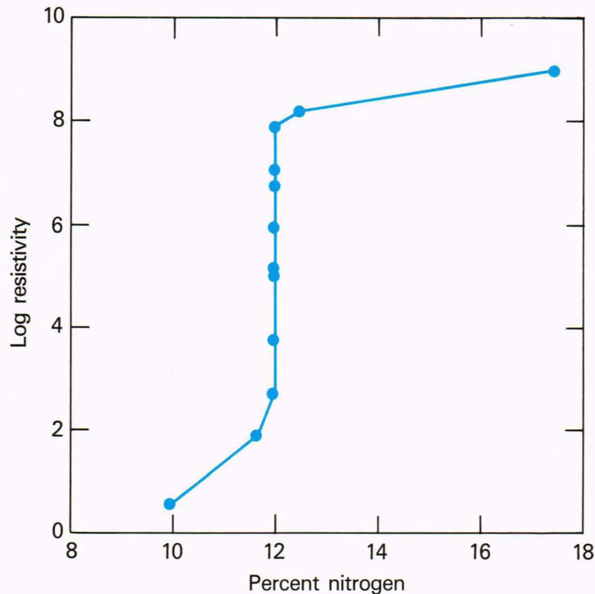


Figure 5—Logarithm of the resistivity versus percent nitrogen in the sputtering gas for a thin film of AlN. A metal-to-insulator transition occurs near 12%, precipitating a change in resistance of about 10 orders of magnitude.

are in a guarded configuration to minimize settling times. The van der Pauw technique[15] is used to determine the electrical transport behavior of the films.

For InN, the target used was 99.999% pure indium metal, and the substrates were randomly oriented single-crystal sapphire or high-purity fused quartz. Sputtering parameters were varied to find optimal conditions. Previous work on InN[16] has shown that sputtering is a very promising technique for depositing material having high carrier mobility. The studies outlined here involve the DC sputtering of a metal target for evaluating the effectiveness of the sputtering system. Experiments began by sputtering indium metal in an atmosphere of pure nitrogen at various pressures. The substrates were held

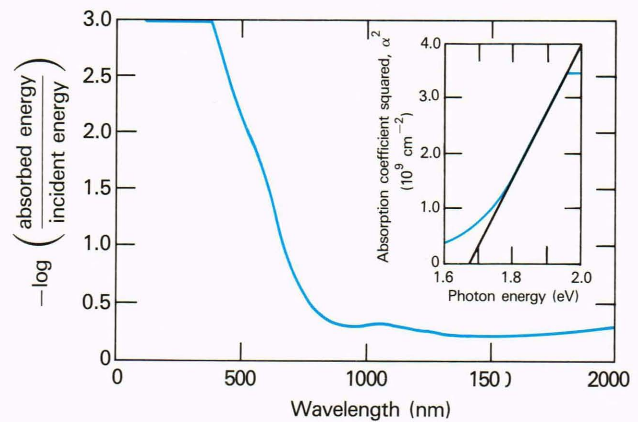


Figure 6—Absorption spectrum of a sputtered thin film of InN. The inset is a plot of absorption coefficient squared versus photon energy. The extrapolated value of the bandgap is 1.7 eV.

at room temperature to minimize decomposition reactions. Figure 6 shows the optical absorption spectrum of a film of InN produced in this way; it is typical of a semiconductor with a 1.7-eV bandgap. X-ray structural analysis reveals that these materials are columnar in nature, with the *c*-axis essentially normal to the film plane. The quality of the films as a function of sputtering pressure was evaluated by measuring the electrical transport properties of the film.

The measurement of film resistivity and Hall coefficient allows the carrier mobility and carrier concentration in the semiconductor to be determined. It is evident in Fig. 7a that a maximal mobility is obtained at a pressure of about 5 μm of pure N_2. This pressure was then used to evaluate the effect of varying the amount of nitrogen in the material by adding argon to the sputtering ambient. As seen in Fig. 7b, the carrier concentration is rising steadily as argon is added to the system, characteristic of increasing nitrogen loss. Figure 8 shows the temperature dependence of the electrical transport properties of InN films. The resistivity of the material increases as the temperature is decreased (Fig. 8a), as is expected of a semiconductor. The carrier mobility improves slightly as the sample cools (Fig. 8b), which is typical of a semiconductor with a high charge-carrier density.

The results of these studies, though promising in some respects indicate that DC sputtering from metal targets will not produce materials of sufficiently high quality for use in semiconductor devices. A logical reason for this failure is best illustrated by referring to Eq. 2. The metal undergoing reactive sputtering does not incorporate enough nitrogen to make a stoichiometric semiconductor. Confidence in RFRMS as a technique for deposition of these materials can be gleaned from the chemical reaction,

$$MN_{1-x} + y/2 \rightarrow MN_{1-x+y} . \qquad (3)$$

If the end product of the chemical reaction of Eq. 2 is used as a sputtering target and is RF-sputtered (neces-

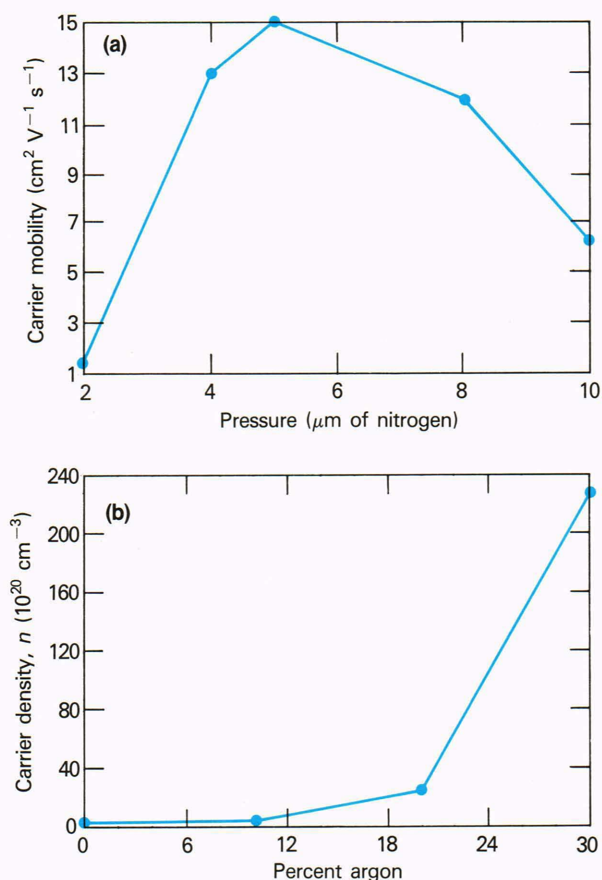


Figure 7—(a) The effect of total sputtering gas pressure (InN sputtered in pure nitrogen) on the mobility of InN, and (b) the effect of percent Ar in the reactive gas mixture at constant pressure (InN sputtered in 5 μm of gas) on the number of charge carriers in InN.

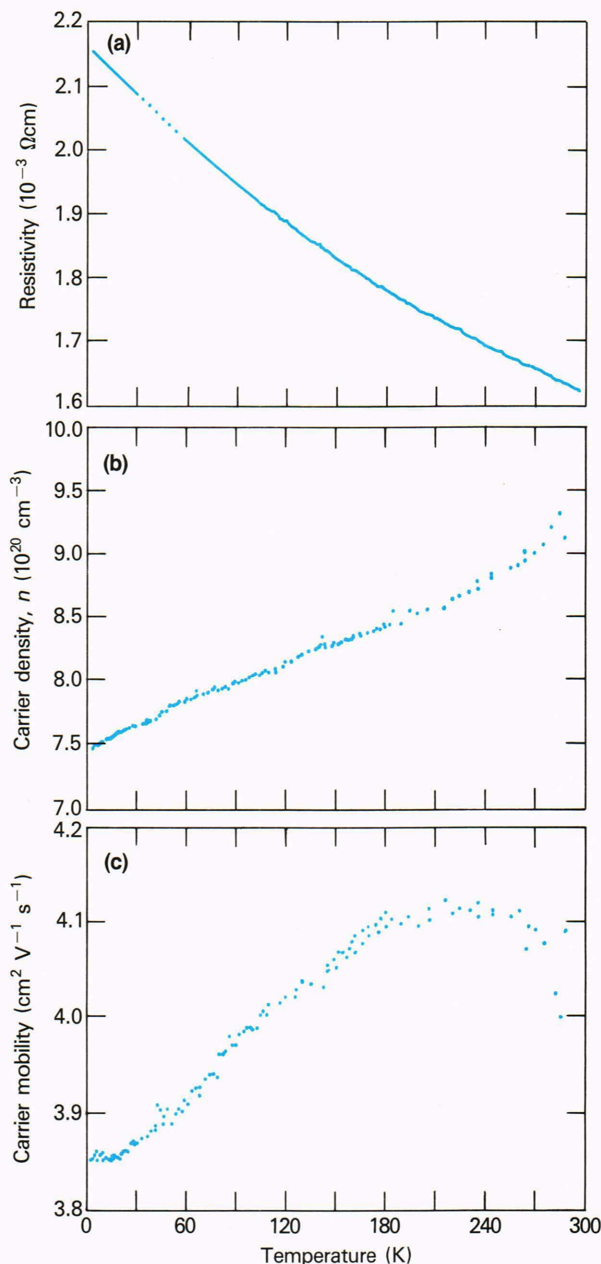


Figure 8—Temperature dependence of (a) resistivity, (b) number of charge carriers, and (c) carrier mobility for a sputtered thin film of InN.

sary because of the nonconducting nature of the material) so that it undergoes the chemical reaction of Eq. 3, then the material will have fewer native defects caused by nitrogen deficiency. This theory has been borne out somewhat by an Australian group who reported producing the highest quality InN to date by using the RFRMS technique on a "nitrided" indium target.[16] Continued similar efforts should produce materials that are vastly superior to those now produced. The RFRMS technique is then a prime candidate for producing high-quality epitaxial semiconductors and superlattices at suitably low temperatures.

METAL-ORGANIC CHEMICAL VAPOR DEPOSITION

As its name implies, metal-organic chemical vapor deposition (MOCVD) is a vapor-growth technology that uses metal-organic precursors as at least one of the constituents of the deposit. It was first developed over 20 years ago, but wide acceptance by the semiconductor community was delayed because metal-organic sources pure enough for device applications were not available. Rapid progress in MOCVD over the last five years has established it as the preferred material-growth technology for a wide range of semiconductor devices, including sources and detectors for fiber-optic communications systems, heterojunction solar cells, mobility-enhanced microwave devices, and various quantum-well structures. MOCVD is now being developed for other material systems ranging from compounds and alloys to superconductors with high critical temperature (T_c).

A typical MOCVD system, configured for the growth of GaAs, is shown schematically in Fig. 9. Liquid trimethyl gallium, $(CH_3)_3Ga$, is contained in a stainless-steel bubbler from which its vapor is transported to the process tube by hydrogen carrier gas. The temperature of the bubbler, and therefore the vapor pressure of

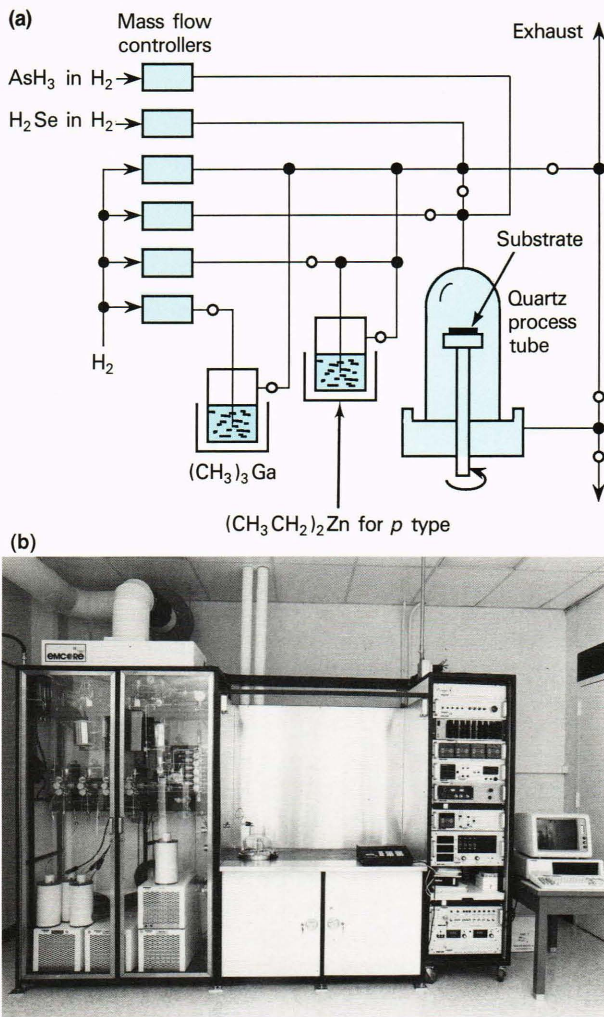


Figure 9—The MOCVD reactor: (a) schematic diagram; (b) photograph.

the metal-organic compound, is closely controlled, so that the amount of vapor is accurately known. The substrate, heated indirectly by either RF or infrared radiation, heats the vapor to the 800 to 1000 K range and pyrolyzes it with arsine (AsH_3) according to the overall reaction,

$$(CH_3)_3Ga + AsH_3 \xrightarrow{\text{heat}} GaAs + 3CH_4 \uparrow . \quad (4)$$

Since the reaction is irreversible, fine control of the growth rate is readily achieved by adjusting the H_2 flow through the metal-organic bubbler.

Carrier concentrations in unintentionally doped material depend on the purity of the starting reagents and are typically below 10^{14} cm^{-3}. Controlled doping is achieved by adding small quantities of appropriate dopants to the gas stream, for example, diethyl zinc, $(CH_3CH_2)_2Zn$; *p*-type, or hydrogen selenide, H_2Se; *n*-type, as shown in Fig. 9a.

The MOCVD effort at APL is based on an Emcore GS3000 reactor (Fig. 9b), which consists of four metal-organic loops, four hydride lines, and hydrogen/nitrogen purge lines. The process tube and pump package is designed to operate in the 6 to 30 kPa range and is capable of holding one 50-mm-diameter substrate per run. During growth, the susceptor rotates at up to 2000 rpm to produce a uniform boundary layer (hence a uniform deposit) over the substrate. The valve sequencing and gas flow rates are managed by an on-board controller. Full-safety interlocks are incorporated into the software to shut the system down safely in the event of power failure, toxic-gas leak, or other potentially hazardous situations.

The abruptness of interfaces between layers of differing alloy composition or dopant concentration is critically dependent on the layout of the gas-handling hardware and the design of the process tube. These devices are assembled to minimize dead space in the pipework and to ensure a rapid change of gas composition over the substrate when multilayer structures are to be produced in a continuous growth sequence. The APL system is designed, as are most others, to operate in a vent/run configuration in which while a particular layer is being grown, the gases required for the next layer are being established in the vent line. The manifold that switches the gases either to the process tube or to the vent line is placed as close to the process tube as practicable. Pressures in the vent and growth lines of systems operating at reduced pressure must be balanced to prevent unwanted pressure surges at the substrate surface during the switching process.

The system is being evaluated, using the growth of undoped GaAs on semi-insulating GaAs substrates as the test vehicle. Growth conditions have been established to produce very high quality material with carrier concentrations of about 10^{14} cm^{-3} and room-temperature carrier mobilities of about 7500 cm^{2}V^{-1}s^{-1}. During the evaluation there is opportunity to measure the electrical properties of the layers routinely. Hall-effect measurements of carrier mobility and carrier concentration at temperatures as low as 1.4 K can be performed using a van der Pauw geometry (results down to 77 K from an early sample are shown in Fig. 10). The residual carrier concentration shown in Fig. 10b is due to sub-ppm impurities in the arsine supply and to the slow leaching of volatile impurities in the system pipework. The reduction in carrier concentration as the temperature is decreased is due to the partial freeze-out of carriers into the shallow parent donor sites. The room-temperature carrier mobility is limited by the scattering of the carriers by polar longitudinal optical phonons.[17] The mobility increases with decreasing temperature because of the $T^{3/2}$ dependence of the polar scattering coefficient, until it peaks at approximately 77 K as limits imposed by scattering of ionized impurities become dominant.[18]

A photoluminescence system—in which carriers are excited by light of higher energy than the bandgap, and the luminescence is detected as the system relaxes to the ground state—is being built, incorporating nitrogen, argon-ion, and excimer-laser sources, a Jarrell-Ash monochromator, and associated detection electronics. Photoluminescence measurements make it possible to de-

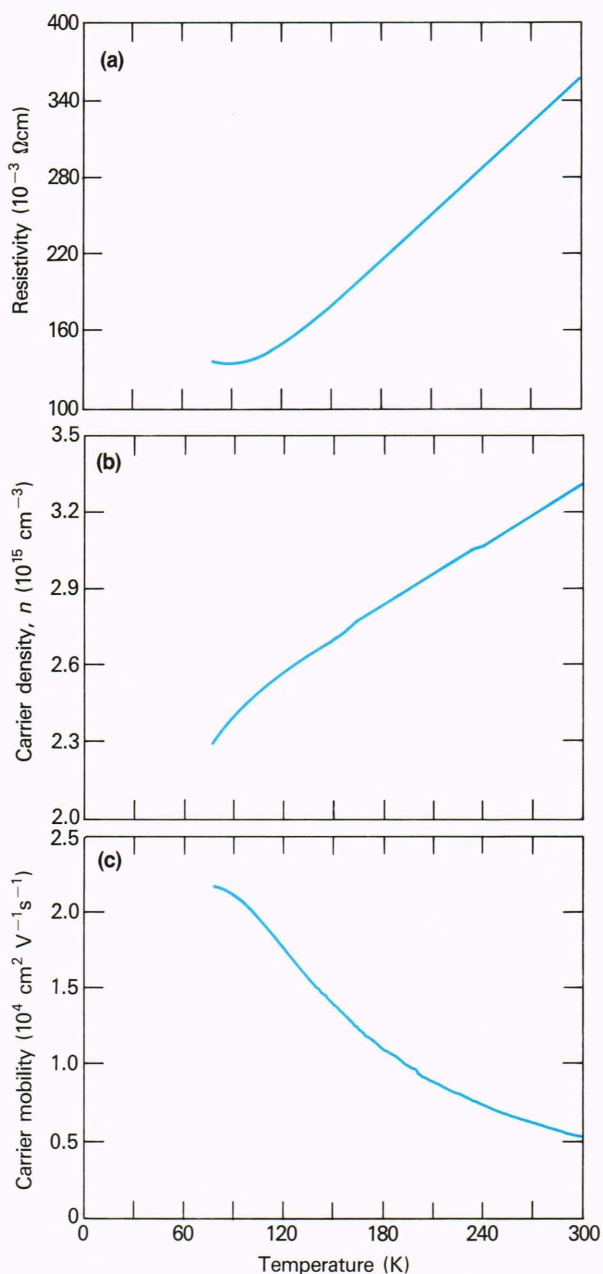


Figure 10—Temperature dependence of (a) resistivity, (b) number of charge carriers, and (c) carrier mobility of a thin film of GaAs prepared by the MOCVD method.

termine such intrinsic properties as impurity levels, minority-carrier diffusion length, and carrier lifetime.[19]

One of the main goals of continued MOCVD effort is to prepare GaN, InN, AlN, and their alloys. A popular method in previous work has been to use trimethyl metal-organics and ammonia (NH_3) as starting reagents. Deposition temperatures for good-quality single-crystal epitaxial growth are in the range 1200 to 1350 K. Lower temperatures have resulted in poor surface morphology and marked deterioration in optical absorption, both indicative of incomplete pyrolysis products or other impurities incorporated into the material.[20] Because ammonia has relatively high thermal stability,

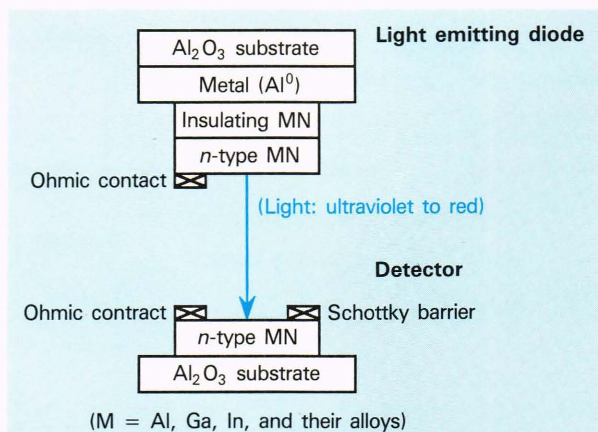


Figure 11—Schematic of a light-emitting-diode source and a solid-state detector fabricated from metal nitrides and their alloys.

NH_3:metal-organic ratios of at least 100:1 and high flow velocities are required to prevent premature pyrolysis of the reactants, particularly for the preparation of samples containing aluminum.

The vapor pressure of nitrogen over GaN is of the order of 10^6 Pa at 1200 K and 10^5 Pa at 1000 K, implying that growth temperatures lower than those realizable with NH_3 could be used to reduce the formation of nitrogen vacancies and hence lead to better quality material. A promising approach is to use hydrazine (N_2H_4), which has a dissociation energy of 60 kcal/mole compared with that of NH_3 at 105 kcal/mole.[21] It is known that species containing oxygen profoundly affect the growth kinetics and the electrical characteristics of GaN, whether prepared by RFMS or by MOCVD. Hydrazine is extremely hygroscopic, and for air at 30% relative humidity, it absorbs moisture at rates of at least 50 ppm per minute of exposure. A quantity of nominally pure hydrazine has been obtained, and further *in situ* purification will be undertaken using an intermetallic (Al,In,Ga) purifier. The gas-handling system and the process chamber of the standard MOCVD reactor have been modified to separate the trimethyl gallium and hydrazine flows before they enter the process tube, a modification that should lead to better control of film deposition by preventing the room-temperature formation of solid addition compounds that interfere with film growth.

DEVICE STRUCTURES

Optical devices with low quantum efficiency can be constructed from material that is not of highest quality. Two simple devices of this sort, based on the materials prepared by the RFRMS technique, have been fabricated. The first, illustrated at the top of Fig. 11, is a light-emitting diode, based on a tunneling barrier deposited between a metal and an *n*-type semiconductor. The device was constructed by depositing onto an aluminum-coated substrate a thin (100-nm) insulating barrier of AlN and then a thick (3-μm) layer of *n*-type AlN. It emit-

ted light weakly and exhibited bistable resistance[22] (switching), presumably because of pinhole defects in the insulating layer. A simple detector, based on either a self-bias using a Schottky barrier contact or an externally generated bias using ohmic contacts,[23] is shown at the bottom of Fig. 11. Detectors based on the metal nitrides have the same advantages as other semiconductor detectors, such as light weight and ruggedness, but with the additional benefit of built-in low-energy cutoff. For example, an ultraviolet detector based on AlN or GaN would not be sensitive to an intense background of visible light that could cause saturation in devices employing semiconductors of narrower bandgap.

Many types of GaAs-based devices, including quantum-well lasers, high-efficiency detectors, and nonlinear optical elements, have been fabricated using MOCVD. At first, some of these device structures will be prepared for use as test objects using GaAs; then analogous devices will be fabricated using the wide-bandgap metal nitrides.

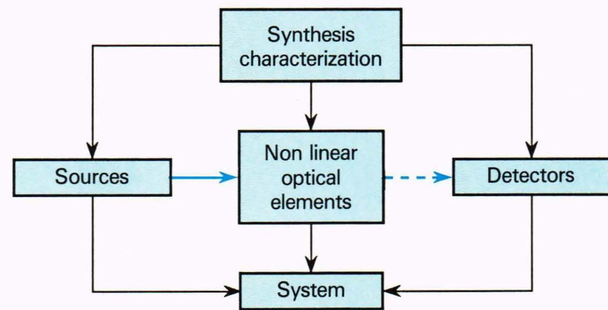


Figure 12—A general photonics system based on metal nitrides and their alloys.

CONCLUSION

A semiconductor system based on AlN, GaN, InN, and their alloys has been identified for study. The physical properties of these materials, notably the bandgap and structure, give promise of application in semiconductor optical devices operating from the red through the visible and into the ultraviolet regions of the optical spectrum. The interactive approach for the study of these materials is outlined in Fig. 12. Two deposition techniques, RFRMS and MOCVD, are in use in the production of device-grade materials. These techniques operate at much lower temperatures than those required for the more conventional methodologies, thus minimizing the dynamic decomposition of the semiconductor as it is being formed. The materials produced will be used to construct optical sources, nonlinear elements, and detectors, in both conventional and novel (quantum-well) structures. It will then be possible to combine the individual devices into an optical system having an operating wavelength that can be matched to the spectral region of interest.

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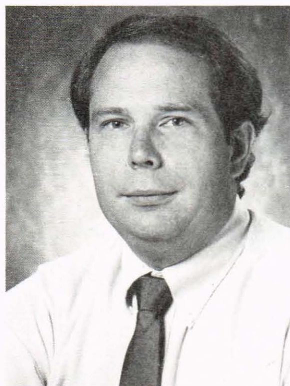

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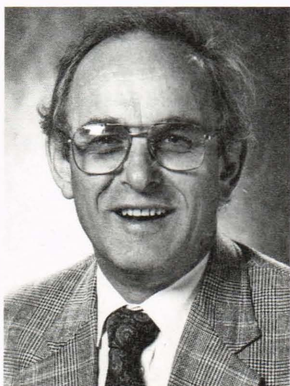

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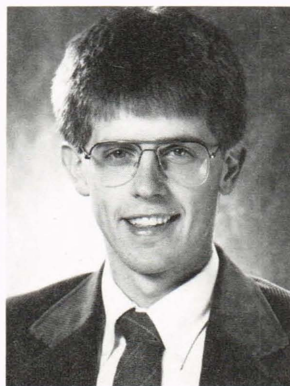

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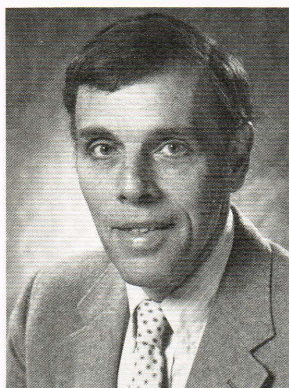

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