7-5 *INVITED*: Computer-Controlled Molecular Beam Epitaxy*

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A most versatile, computer-controlled MBE system[1] has been developed for preparation of sophisticated device structures involving multiple layers of semiconductors and metals. Figure 1 shows a schematic diagram of this system, including source-shutter and substrate-heater assemblies, a spectral mass analyzer for monitoring each beam intensity providing input data for an IBM System 7-1130 process control computing system, and high energy electron diffraction in situ during growth for examination of surface smoothness and ordering. Our ultrahigh vacuum pumping station has the capacity of a pumping speed of more than 45,000 litre/sec. It has been well documented that the growth process in MBE governed by kinetics is far different from conventional techniques such as liquid-phase epitaxy, chemical vapor-phase deposition, etc., which proceed near thermodynamic equilibrium conditions. In performing MBE in the ultrahigh vacuum environment, the epitaxy temperature is considerably lower than that in the other techniques and also it is possible to achieve the extreme surface smoothness. These facts make it possible to produce epitaxial layered structures where the impurity distribution or the alloy composition is rapidly changing in space. With our system using five effusion ovens for vapor species: Ga, Al, Mg, Ge, and As_2 (or As_4), we have successfully grown $Ga_{1-x}Al_xAs$ multilayer structures of high-quality on heated GaAs substrates. By continuously processing the instantaneous value of each beam intensity, the computing system controls each oven temperature (thus each beam intensity) and commands the whole shutter operation (each oven has its own shutter) to produce a desired structure. Thus this technology enables us to successively grow one layer to another with sharp transition and also to precisely control the thickness, the alloy composition, and the doping level of n or p in each layer. We also have achieved epitaxial growth of alternating thin films of GaAs and pure Al metal on GaAs substrates having a particular crystallographic relationship.

Esaki and Tsu[2] predicted a quantum mechanical effect - a strong nonlinearity in transport properties including a negative resistance, in a superlattice structure having a one-dimensional periodic potential in a monocrystalline semiconductor. In order to observe the effect, resulting from the interaction of electron waves with the periodic potential, a superlattice period is required to be shorter than the electron mean free path. With our system, $Ga_{1-x}Al_xAs$ superlattice structures of 40 - 100 periods each 70 - 80 angstroms thick were grown by a periodic variation of alloy composition between $x = 0$ and 0.3 - 0.5. The photographs in Fig. 1 illustrate the growth of this structure. Among a number of analytical techniques employed for evaluation of our multilayer structures, two most novel ones are nuclear backscattering with 2.5 MeV He ions and Raman spectroscopy with an Argon ion laser. Transport properties in the direction of the superlattice were measured by attaching a small ohmic contact on the surface. We have observed a symmetrical,

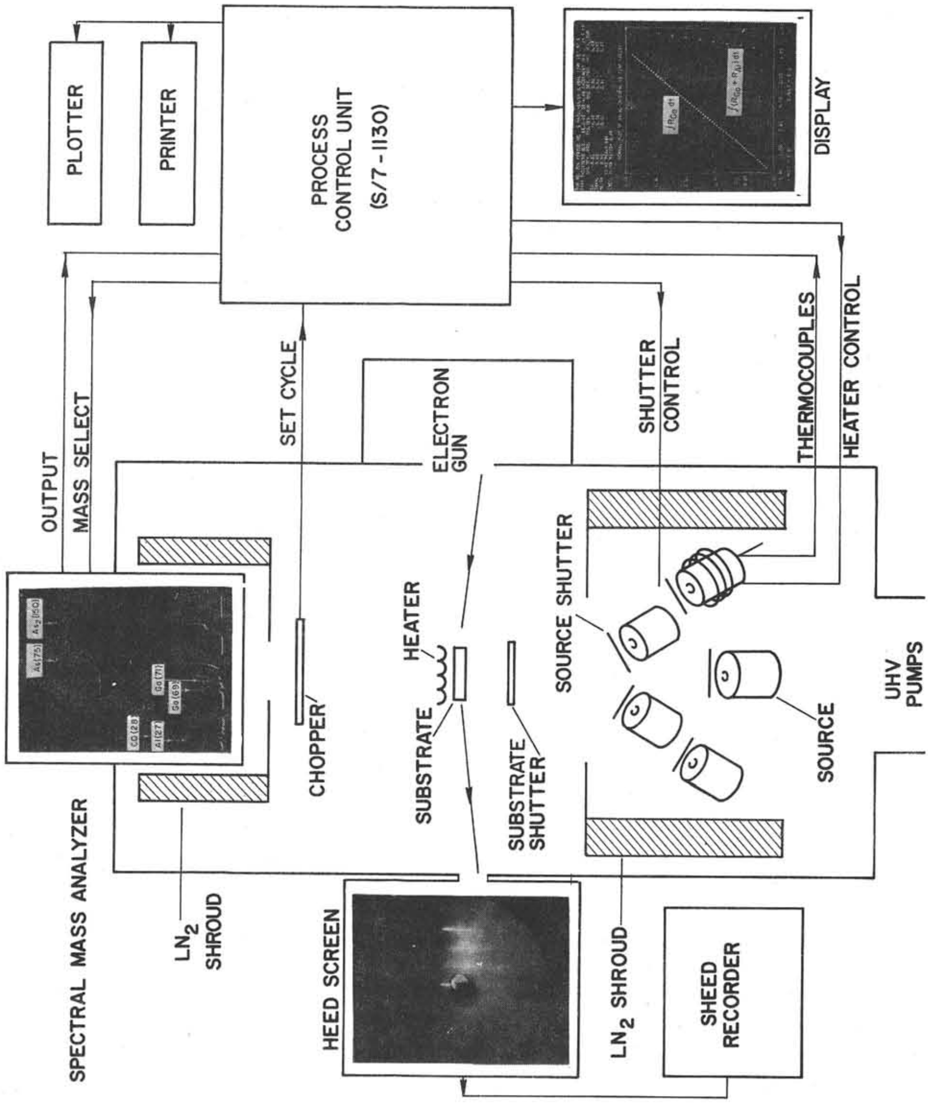

Fig. 1 A schematic diagram of the computer-controlled molecular beam epitaxy system.

nonlinear current-voltage characteristic: some of the units exhibit an N-shaped negative resistance.[3] This observation is analyzed in the framework of the previous theoretical treatment. Recently, we have made an attempt to fabricate GaAs-$Ga_{1-x}Al_xAs$ double-heterojunction laser diodes; preliminary results of this work will be mentioned.

1. L. L. Chang, L. Esaki, W. E. Howard, and R. Ludeke, J. Vac. Sci. Technol. 10, 11 (1973).
2. L. Esaki and R. Tsu, IBM J. Res. Develop. 14, 61 (1970).
3. L. Esaki, L. L. Chang, W. E. Howard, and V. L. Rideout, Proc. 11th Int. Conf. on Physics of Semiconductors, Warsaw, Poland, p.431.

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