Electron beam source molecular beam epitaxial growth of analog graded $Al_xGa_{1-x}As$ ballistic transistors

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A new method has been developed for the growth of graded band-gap $Al_xGa_{1-x}As$ alloys by molecular beam epitaxy which is based upon electron beam evaporation of the group III elements. The metal fluxes are measured and feedback controlled using a modulated ion gauge sensor. The system is computer controlled which allows precise programming of the Ga and Al evaporation rates. The large dynamic response of the metal sources enables growth of variable band-gap III-V alloys with arbitrary composition profiles. This new technique is demonstrated by synthesis of analog graded $Al_xGa_{1-x}As$ unipolar ballistic electron transistors.

The optical and electronic properties of $Al_xGa_{1-x}As$/ GaAs heterojunctions and quantum wells have been extensively studied in materials grown by molecular beam epitaxy (MBE). There are, however, a number of interesting structures which have been proposed which require precise alloy grading over atomic dimensions. The ability to tailor band structure to obtain novel electrical and optical properties is termed "band-gap engineering." [1] Previous attempts to obtain alloy grading by varying the temperature of MBE effusion cells have been only marginally successful and have serious limitations.[2-4] This is related to the large thermal inertia and restrictions in heating and cooling rates of the MBE effusion cells which leads to slow modulation of the beam flux along with a time lag in response. In addition, variations in the growth rates determined by the group III molecular beam fluxes seriously complicate the problem of obtaining arbitrary alloy grading. Thus group III sources with large dynamic response are required for band-gap engineering of $Al_xGa_{1-x}As$. Several different approaches could be used which include electron beam heated sources which are typically used to evaporate Si and refractory metals,[5] gas sources,[6] and ion beam sources.[7]

We recently reported on the use of electron beam source MBE growth of III-V compounds.[8] In this letter, we discuss the use of this technique for precise analog grading of $Al_xGa_{1-x}As$ and its application in the growth of unipolar ballistic electron transistors. We observe, for the first time, ballistic electron transport by hot-electron spectroscopy in graded $Al_xGa_{1-x}As$ barrier transistors.

The MBE system is a vertical design which is necessitated by the use of the electron beam evaporation sources and is similar in design to systems used for silicon or metals epitaxy. Three electron beam sources are used to evaporate Ga, Al, and In since these elements determine the alloy composition in III-V compound semiconductors grown by MBE. A large capacity, 300 cc, arsenic source with a high-temperature cracker is used to generate an As_2 molecular beam. A Si strip heater and small 2 cc Be effusion cell are used as n- and p-type doping sources, respectively. All the molecular beam sources have separate mechanical shutters which are computer controlled. A substrate manipulator which allows substrate heating and rotation is located 300 mm above the

source flange. Indium-free wafer holders for 50 and 75 mm substrates can be fitted on the manipulator.

The geometry of the electron beam sources, flux sensors, and substrate is shown in Fig. 1. Each of the electron beam sources has its own flux sensor which consists of an ion gauge contained within a liquid-nitrogen cryoshroud. Each sensor "looks" at the electron beam sources through a series of apertures, and a rotary chopper blade is placed in front of the ion gauge to obtain differential measurement of the beam flux through subtraction of the background pressure in the gauge. The analog signal from the flux sensor is absolutely calibrated with the growth rates determined *in situ* by reflection high-energy electron diffraction oscillations.[9] The analog signal from the flux sensor is input to a digital controller in a feedback control loop which regulates the electron beam power supply. The digital controller is interfaced with a computer which updates the growth rate set points every second and also controls shutter openings and effusion cell and substrate temperatures.

The dynamic response of the Al source evaporation rate is demonstrated in Fig. 2. The source was programmed to follow a sawtooth profile with linear increasing and decreas-
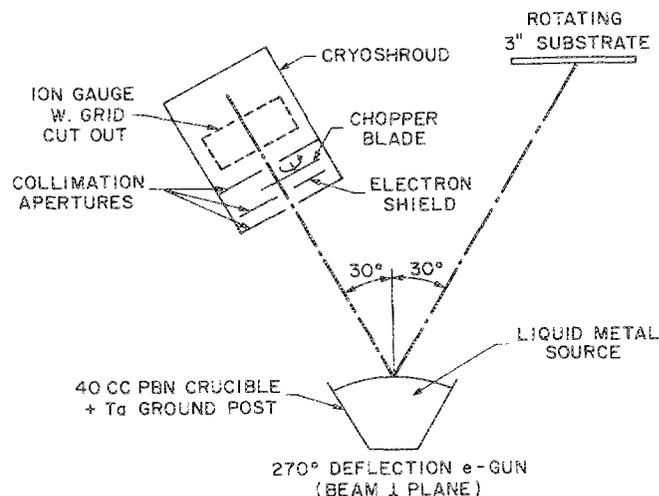

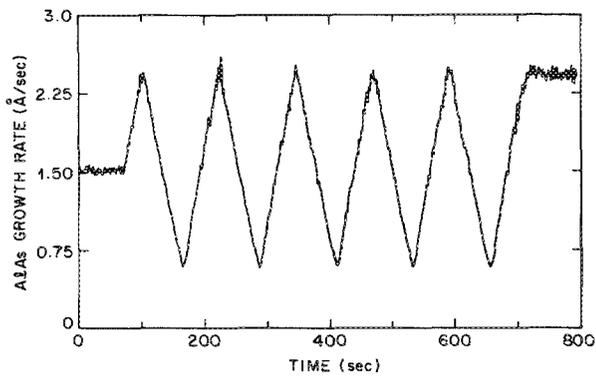FIG. 1. Schematic diagram of the electron beam source geometry in the MBE system.

FIG. 2. Output control signal response of Al source to a programmed saw-tooth evaporation rate profile.

FIG. 4. Derivative collector current vs collector voltage in the graded band-gap ballistic transistor. The high-energy ballistic peak is centered near $V_{CB} = 0.6$ V. The low-energy peak, centered near $V_{CB} = 3.6$ V, arises from electron heating of the Fermi sea of electrons in the transistor base.

ing evaporation rates. It is seen that the Al source accurately tracks the programmed profile without phase lag and there is no overshoot of the peak set point or undershoot of the valley set point. This profile was obtained during continuous growth, something which would be impossible to obtain by use of conventional effusion cells. The electron beam sources have also demonstrated controlled evaporation rates down to 0.01Å/s and changes in the evaporation rate between 0.01 and 10 Å/s have been achieved in less than 10 s.

An $Al_x Ga_{1-x} As$ unipolar hot-electron transistor was grown by e-beam source MBE using analog grading for the emitter and collector barriers. A secondary ion mass spectroscopy (SIMS) profile of the Al alloy composition in the electron barriers is shown in Fig. 3. The structure was designed with a collector barrier peak of $x = 0.35$ and an emitter barrier peak of $x = 0.3$. The long and short arms of the graded barrier were 1000 and 90 Å, respectively, with a barrier peak width of 50 Å. The emitter, base, and collector were doped n type to 1×10^{18} cm^{-3} and the graded barriers to 1×10^{16} cm^{-3}.
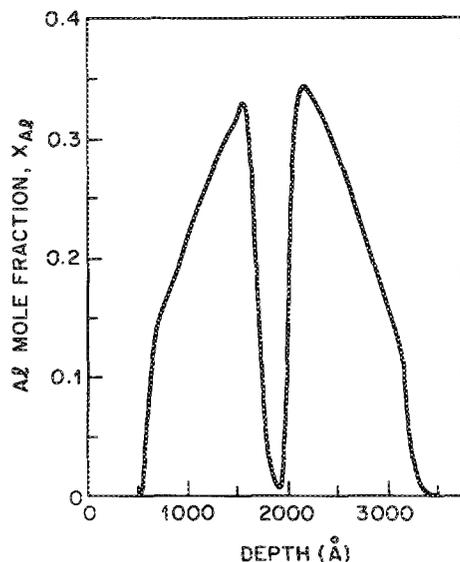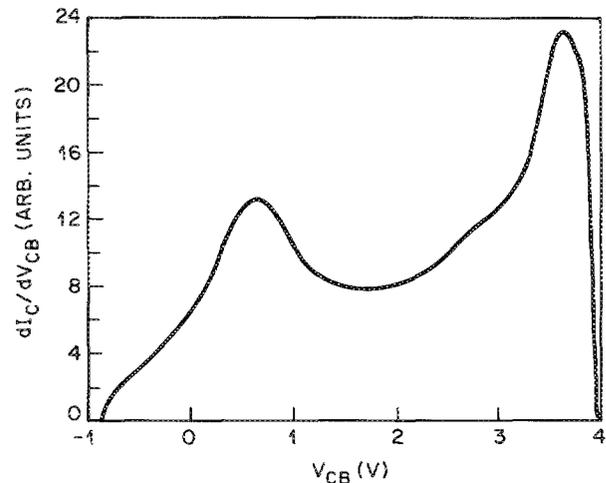

FIG. 3. SIMS depth profile of Al composition in the graded band-gap ballistic transistor.

Mesa transistors were fabricated using anodic etching to the base and wet chemical etching to the collector followed by an alloyed Au/Ge/Ni metallization for contacts. Hot-electron spectroscopy[10–12] was performed on a transistor with a base width of 400 Å at 4.2 K. The derivative spectrum of collector current shown in Fig. 4 clearly shows evidence of a "ballistic" electron peak centered at $V_{CB} = 0.6$ V. This is the first time that ballistic transport has been seen in analog graded $Al_x Ga_{1-x} As$ structures. It should be noted that in a number of attempts to simulate alloy grading by using variable duty cycle chopped $Al_x Ga_{1-x} As$/GaAs superlattice,[13] no ballistic peak was observed. We infer from this that the multiple interfaces or trapped impurities at the interfaces in the chopped superlattices lead to enhanced electron scattering suppressing ballistic transport. In addition, the ballistic peak for the graded band-gap $Al_x Ga_{1-x} As$ transistor has a width of around 50 meV compared to a width of around 85 meV measured in earlier work on planar-doped barrier transistors.[10] The reason for the larger broadening in the planar-doped barriers is due to statistical fluctuations in acceptor point charge locations within the barrier leading to barrier height fluctuations. Our own calculations and those of others[14] have shown that these barrier height fluctuations have a root-mean-square value of about 35 meV. However, potential fluctuations in graded $Al_x Ga_{1-x} As$ barriers are estimated to be on the order of 3 meV. Thus our graded $Al_x Ga_{1-x} As$ barriers give much better resolution for use in hot-electron spectroscopy.

Monte Carlo simulations of our hot-electron spectra[15,16] suggest that, in addition to a sharp peak at the injection energy, a second "echo" peak should occur in the hot-electron spectrum at the average energy loss below the injection energy. Experimentally, we observe a broad peak in the spectrum containing electrons both above and below the injection energy and no sign of the expected echo peak. It has recently been suggested that this broadening (which, as discussed above, is unlikely to arise from barrier height fluctuations) is due to a streaming plasma instability[17] well known in gase-

ous plasma theory[18] but never before spectroscopically measured in a semiconductor. Another possible explanation is that the finite lifetime $\tau \sim 3 \times 10^{13}$ s^{-1} of injected electrons leads to an energy broadening $\hbar/\tau \sim 20$ meV in the measured spectra. We note that this fundamental effect is ignored in the usual, semiclassical, Monte Carlo simulations of hot-electron transport in device structures.

In conclusion, we have developed a new technique for precise alloy grading of $Al_x Ga_{1-x} As$ using electron beam source molecular beam epitaxy. This new method has been used to synthesize a graded band-gap hot-electron transistor in which we have observed ballistic transport using hot-electron spectroscopy. This new e-beam MBE method will have significant application for analog alloy grading $Al_x Ga_{1-x} As$ device structures including unipolar and bipolar transistors and in parabolic and V-shaped tunneling superlattices.

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