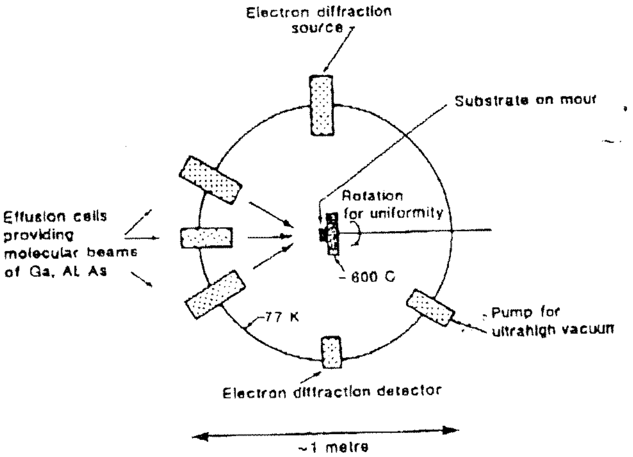
IIB CRIBS
2003

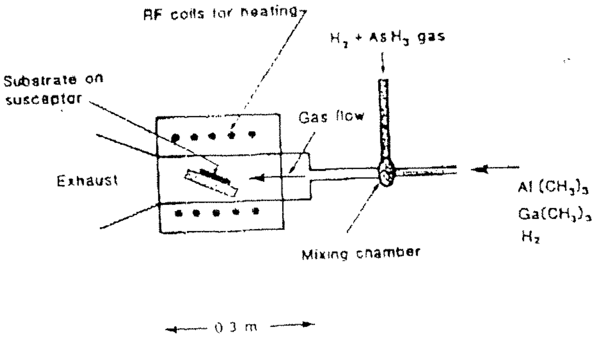
4B18

Module B18
Model Answers

Q1: (a)
Expect diagram of MBE and MOCVD apparatus with an indication of their respective size.



(a)



(b)

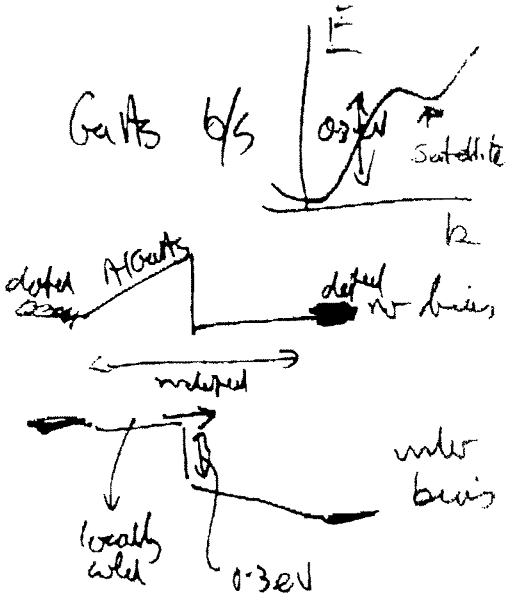
MBE a very highly controlled evaporation process under ultra-high vacuum conditions. Atoms or molecules are ejected from high temperature Knudsen cells and strike the heated wafer a
Good in situ diagnostics. Flux rates of atomic or molecular species from Knudsen cells must be calibrated, and the relative partial pressures of group III and group V elements controlled to get stoichiometric growth.
Typical growth rate 1 atomic layer per second or one micron per hour.
Shutters in from of cells are used to turn beams on and off and change composition of crystal on the scale of 0.1s or 0.1 monolyaer.
Separate cells contain dopants heated to give much lower fluxes: again these fluces are controlled by shutters. Need two cells if step changes in doping profiles are needed as in HBT collectors etc.

MOCVD a form of cracking. Precursor gases (e.g. trimethyl gallium and arsine are mixed and diluted in a hygrogen carried and passed over a substrate which is heated by an rf induction coil. There is a surface reaction that produces GaAs and methane, the latter being swept out.
The growth rate is typically 10 times faster than MBE. There are no in-situ diagnostics. The system is easier than MBE to scale up fro production, and is used almost exclusively for optical devices. The major concern is safety associated with the gases, and this involves a major cost overhead.
Again appropriate precursor gases – diborane or dimethyl zinc are used for doping.

Q2(b)

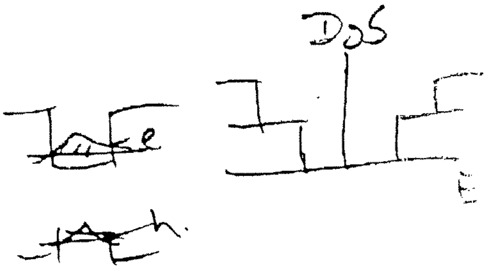
(i) Heterojunction Gunn device – a graded composition layer is used to heat up the electrons in the quasi-electric field, keeping the electrons locally cold as the band-edge rises until an abrupt heterojunction is used to launch the electrons into the satellite valleys of the gallium arsenide conduction band. This removes the optical phonon losses that arise in a conventional high-field region in GaAs. The efficiency increases.

The intervalley transfer occurs near the heterojunction and this reduces the noise compared with a conventional high-field device in GaAs where the position of the intervalley transfer occurs depends on the degree of optic phonon losses. Electrons after transfer are at 3000K, and whether the lattice is at 300K or 400K is less important – the temperature dependence of this device is much reduced.

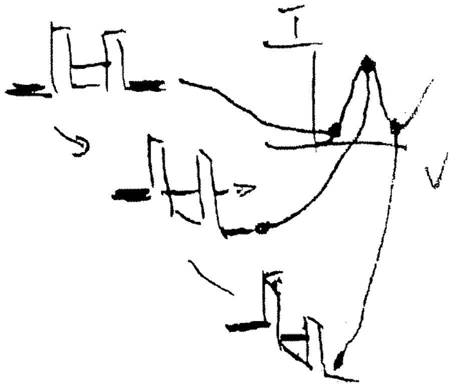


(ii) Quantum wells confine carriers so that overlap of wavefunction is greater and optical matrix elements are improved. The 2D density of states is easier to invert, meaning a low threshold current density.

The quantum well width and depth can be used to tailor the operating wavelength.

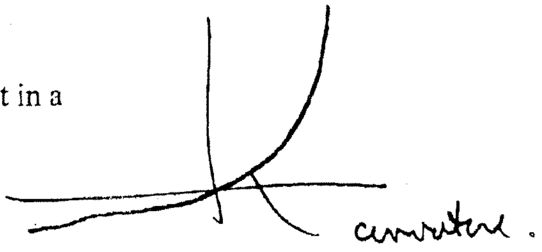


(iii) The double barrier resonant tunnelling structure with doped contact layers on either side can produce strong negative differential resistance under bias as the energy of the quasi-bound level in the well passes through the range of energies of occupied states in the emitter. With high quality barriers and wells, one can achieve 50% conversion efficiency from dc to rf power at low frequencies and fundamental mode operation to 700Ghz.

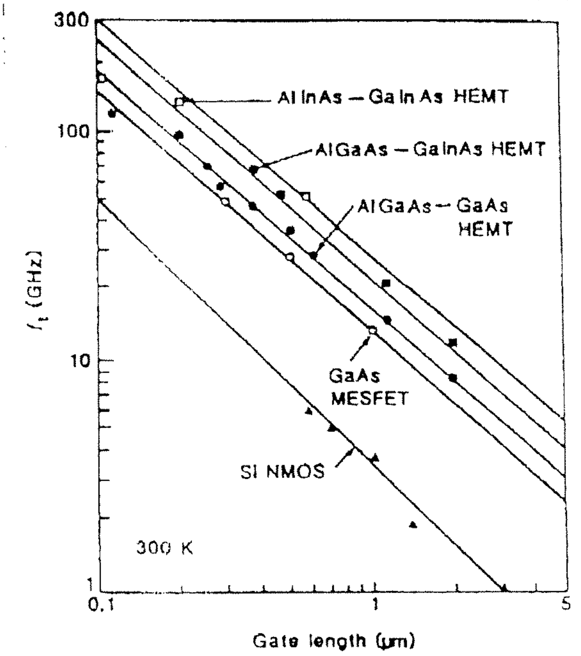


(3) (a) Curvature in the I-V characteristics.

The 2nd order term in the Taylor expansion of the I-V characteristics is a prefactor in the increase in dc current in a microwave detector.



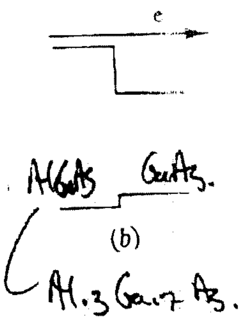
1(b) See diagram that shows the evolution of cut-off frequency as a function of gate length as one moves from silicon to GaAs mesfet (x3), to various HEMT structures that use stained layers, higher band offsets etc (another factor of 3).



Power handling not greatly improved as always dealing with a thin channel. There are some ideas of dual channels and ulta-high-doping in GaN/AlGaN systems that improve power handling.

The InAlAs/GaInAs HE~~M~~MT is the quietest semiconductor device available, for reasons that are not entirely clear, and it forms the basis of low noise amplifiers for direct-broadcast-by-satellite receivers etc. Only bolometric systems for extreme uses are quieter.

Q2(a)
See diagrams for
Hot electron injection
Quantum confinement
Resonant tunnelling

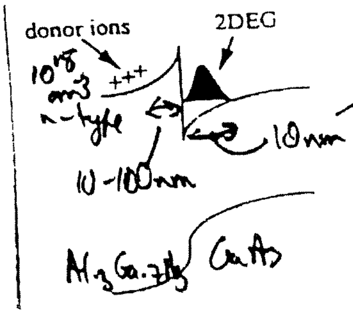


(b)

↕ ΔE ~ 0.3 eV

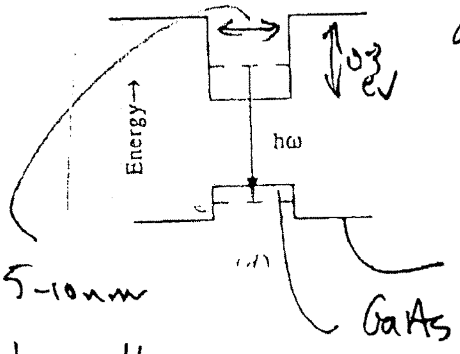
doping modifies the diagram, but does not change the principle.

Can get ΔE ~ 0.5 eV or more with GaInAs | AlInAs.

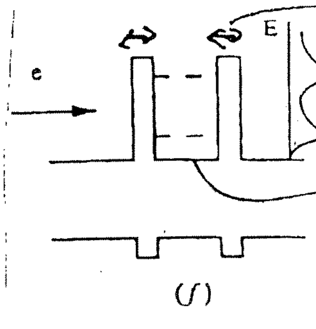


(c)

HEMT quantum confinement



quantum well quantum confinement



(f)

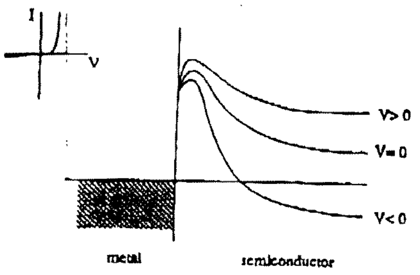
Resonant tunnelling 3-5-10 nm

3 - 10 nm

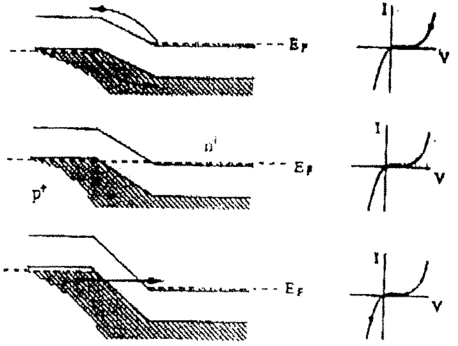
undoped — doping in contact layers for device

3(b)

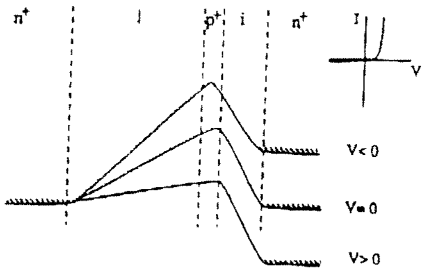
Schottky diode



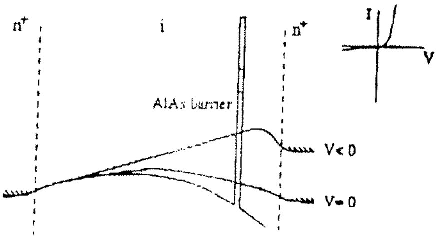
Backward diode



Planar-doped-barrier (PDB) diode



Asymmetric SPAcer-layer Tunnel (ASPAT) diode



Schottky- intrinsic barrier at metal-semiconductor interface – asymmetric density of states gives asymmetric current. Curvature highest when biased to height of Schottky barrier.
Planar doped barrier – height and asymmetry of barrier determined by doping-thickness product of the p+ layer and the relative position wrt the contact layers respectively.
Backward diode – asymmetry determined by different density of tunnelling states under forward and review bias.
ASPAT diode, asymmetry determined by position fo tunnel barrier.

3(c) Basic transfer efficiency from input power to DC terminal voltage, and the dynamic
The backward diode exhibits NDR in forward bais which limits the range of bias over which the device can operation.
The backward diode has almost no temperature dependence, the ASPAT a lown temperature dependence, as both depend on tunnelling.
The PDB and Schottky rely on thermionic emission and both have a strong temperature dependence, although the Schottky is the stronger of the two.
The tunnel devices have lower added noise as the electrons are less heated, and the ASPAT and PDB have a high resistance to thermal breakdown under intense pulses as the contacts are ohmic and in the low field part of the device.

Q4(a)

Advantages of a wide band-gap emitter:

(i) higher emitter efficiency as less reverse injection of holes

(ii) decreased base resistance as higher doping in the base can be tolerated without sacrificing emitter efficiency

(iii) less emitter current crowding as there is a lower lateral voltage in the base,

(iv) improved frequency response from higher current gain and lower base resistance, and

(v) wider range of temperature operation – up to 350C and down to 4K.

Sketch for GaAs/AlGaAs devices.

F_Ts above 100GH impossible without heterojunction.

(b) Johnson criteria: $V_M f_T = E_B v_s / 2\pi$

$PZ(f_T)^2 = (E_B v_s)^2 / 32\pi^2$

(E_B= dielectric breakdown field, v_s=saturated drift velocity: both materials properties.) V_M=maximum voltage across a devices, f_T the transit time limited operating frequency, P the output power into a load impedance Z.

The materials figure of merit for GaAs is $6 \times 10^{12} Vs^{-1}$.

For a device with an f_T of 1000Ghz, VM is 1V.

This means low bias operation, and the PZ product is appoximately 0.1, meaning output powers of order 2mW. i.e. low power.

The saturated drift velocity is of order 10^5m/s, so that the active device length is only 0.1μm. There is limited functionality that can be encompassed in such as small length. The practical problems include very low resistance ohmic contacts that are required to get a satisfactorily small RC-time constant. The small C is achieved by very small device area, which again places limits on the power handling.

Q5 (a) Note that the figure of merit (see Q4(b)) for GaN is 10 times bigger, meaning that 10V bias and 0.2W are feasible in principle. This is because of a factor of a 50% increase in v_s and a 6 fold increase in E_B. Hence the rush in research on this material.

The problem is that the material as grown is still very full of defects, e.g. 10^9 threading dislocations per square centimetre, up by 5-6 orders of magnitude on GaAs. The optical and electronic device results to date seem to be in spite of this level of dislocation. There are also very strong piezoelectric effects associated with GaN, especially when strained. The 2DEG can be achieved without modulation doping, as the strain fields result in energy band diagrams that populate the two-dimensional electron gas without needing doping in the AlGaN layer.

(b) References papers handed out in lectures.

The transistors are already superior in power handling to their GaAs and InGaAs/AlGaAs equivalents, but they fall short of the theoretical limits because the materials quality and the contact technologies are still quite primitive.