PART IIB 4B18 ADVANCED ELECTRONIC DEVICES PROF M J KELLY

CRIBS AED2010 : sketches photocopied at end.

Q1:

(a) Standard sketch of MBE chamber and MOCVD reactor, noting the elements, sample stage and susceptor respectively, high vacuum versus low pressure system, evaporation versus cracking, slower versus higher throughput, slower versus faster growth rate and higher versus lower precision, low electronic versus optical defects, more versus less techniques for in-line monitoring, competing elements of cost (more steelwork and pumping versus simpler system but massive safety costs), comparable costs per wafer. 30%

(b)

(i) the quality of interfaces:
TEM for steps, interface roughness
Photoluminescence linewidth for quantum well uniformity
Import for HEMT and laser devices.

(ii) the uniformity across a wafer
X-ray peak angles as a sign of drift across wafer for composition
Infrared absorption as sign of drift in doping composition
Important for yield of all devices

(iii) the doping profile as a function of depth from the surface,
SIMS monitoring the dopant
Important for HBTs and most diodes

(iv) the composition of a tunnel barrier layer and
TEM from detailed modelling of diffraction images
SIMS monitoring the elemental composition through the barrier
Important for any tunnel barrier

(v) the width of a quantum well.
TEM as with (iv)
SIMS as with (iv)
Photoluminescence energy.
Important for laser and infrared devices. 40%

(c)

GaAs versus GaN

Main issue the band gaps	GaAs 1.4eV in the infrared
	GaN 3.4eV in the blue

The quality of the GaN is lower (higher defects) than GaAs.
GaAs over GaN: anywhere where the GaAs performance will do, as it is a simpler materials system to growth, cheaper devices can be made, yield is higher etc.
For short wavelength devices, and very high power devices and higher temperature devices, and highest speed devices, the increased bandgap and the higher saturated drift velocity of GaN over GaAs gives a factor of about 15 in the Johnson criterion (frequency-voltage product) and 200 in the second Johnson criterion (frequency square versus output power product). 30%

Q2 ASPAT diode
(a) Standard diagrams from the notes (15%)

(b) Purpose of layers (40%)
1 Substrate
2 doped layer for bottom contact (thick enough to ease etching end-point from the top surface) and chance for layer to lose any defects from the substrate
3 low doped so that modelling of device is more accurate in terms of the interface from low to no doping,
4 short lever arm of the asymmetric device
5 the key tunnel barrier that determines the level of current achieved
6 long lever arm of the asymmetric device
7 low doped so that modelling of device is more accurate in terms of the interface from no to low doping,
8 top contact layer, thick enough not to have to worry about metal punch through in processing.

(c) The most important layer in setting the level of current for a fixed bias, and also this current level is extremely sensitive to the uniformity of this layer thickness on every lateral scale above about 10nm. None of the techniques of growth to date can ensure the level of wafer-to-wafer reproducibility to allow for low cost manufacture, and even the in-wafer uniformity is hard to achieve to produce identical devices. (15%)

(d)
Three other devices
(i) Schottky diode: thermionic emission gives high temperature sensitivity, contact between polycrystalline metal and semiconductor the source of noise
(ii) planar doped barrier diode: thermionic emission gives high temperature sensitivity (although charge spill over at high-low doped interfaces contrive to reduce the temperature dependence, lower nose from ohmic contacts well away from the high-field regions.
(iii) germanium backward diode
Tunnelling device and extremely low temperature dependence and low noise. There is a limited dynamic range set by the Ge band gap.

Q3:

(a) Primary mechanism: under high electric fields, electrons in the conduction band are accelerated up the bandstructure, so that intervalley transfer eventually takes place from central low mass, low scattering rate conduction band valleys to high mass, high scattering rate satellite valleys resulting in lower current for same applied field. See diagram.
In n+ - n- - n+ structure, the high field is in the n- region. Although we start out with a uniform charge density, once intervalley transfer takes place the intervalley electrons move more slowly, resulting in a drop in electron density ahead of a pile up in electron density, i.e. a spike in electron density builds up as it progresses along the n- region delivering a spike in current at the end, after which the electron density returns to being uniform, waiting for intervalley electron transfer to start again. (See diagram at end) The result is a series of current spikes, with much energy in the high harmonics. There are refined tricks to try to broaden out the spike and put more of the energy in the first harmonic.

(b) Graded composition layer of $Al_xGa_{1-x}As$ with x increasing from 0 to 0.3 over 50nm (with an abrupt return to x=0), represent a rising conduction band edge which the high field reduces to nearer flat bans. Under the high field the electrons in the conduction and remain cold as they cross the graded layer, until they reach the heterojunction – they are injected hot into the upper conduction band, and have little chance to emit optic phonons before scattering into the satellite valleys. Optic phonon emission is the countering energy-loss process when electrons are being heated by an electric field. This results in (i) greater efficiency of intervalley transfer, (ii) less noise as most of the intervalley transfer takes place very close to the heterojunction, and not further down the transit region after multiple phonon emissions processes, and also less of a temperature dependence, as all the electrons are emitted at ~3000K, and the sensitivity to the lattice temperature (3250-400K) is reduced. All have device advantages.

(c) There is no wider-gap analogue in the InP materials system. In principle, one could apply the same idea to the GaN/AlN system but no GaN Gunn diode has yet been made, as the stability of contacts under the required very high fields and currents have not been established, even for pulse mode operation.

Q4:

(a): Generation of microwaves required negative differential resistance
Detection of microwaves required curvature in the I-V characteristics.
$\Delta V \Delta I$, the product of the voltage and current rages of the negative differential current regime, is proportional to the power that can be delivered from the device, while the second Taylor coefficient d2I/dV2 is proportional to the detectivity of a detecting diode. Diagrams below.

(b) For a double barrier source: thin high barriers, and a well that is thick enough to have the first bound state as low as possible. The former give high current and ΔI, which the latter minimises the voltage at which the onset of NDR occurs.
For AlAs/GaAs system one can get just under 10mW out to 100GHz and then a fall-off at higher frequencies. Using InGaAs/InAlAs one can get slightly higher values out to 200GHz, before a 1/f2 drop-off.

(c) A transit layer at the anode gives a lever arm effect for the voltage: for 0.1V across the double barrier region, one might need 1V across the whole diode. This allows one to expand the V axis and the ΔV region. Typically 0.1mm might be placed after the diode. The main negative side effect is that the time to cross the transit region then represents the inverse of the upper frequency, which is typically reduced from THz to 100GHz or less. One can get 10mW of power out to 100GHz with 50% efficiency by this means.

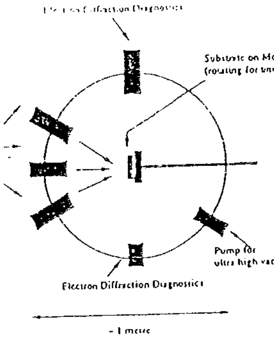
Q5:
(a) Wide gap emitter allows
(i) higher efficiency injection of electrons into the base with a suppressed reverse injection from the base into the emitter because of the heterojunction band-gap discontinuity.
(ii) higher doping is possible in the base without reverse injection reducing the base current
(iii) higher frequency operation occurs because of reduced base resistance
(iv) lower base resistance leads to lower current crowing around the perimeter of the device as a lower lateral bias can be supported within the base, and
(v) devices can be operated at lower temperatures without carrier freeze out and at higher temperatures without thermal runaway compared with a homojunction bipolar transistor.
All five advantages are achieved in practice, which is why HMTs are ubiquitous.

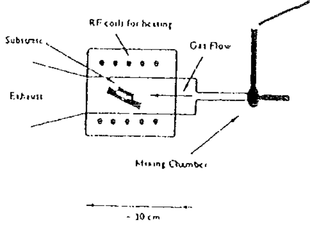
(b)
HEMT: all the effort is in precision lithography for the gate region.
HBTs place emphasis on the layer thicknesses to get the high performance, but the processing that involves revealing the three separate layers (emitter, collector and base) and making highly selective contacts to each layer is a much greater overall challenge.

(c) Moore's law is the codification of the observation that the number of transistors on a single chip double about every 28 months. At present commercial devices are based on 60nm gate lengths for CMOS transistors. Although devices with gate-lengths down to 10nm have been made, the control over yield and uniformity of performance have not get achieved the levels needed for commercial production.
Already there are moves to sue other ways of rating chips, such as they overall performance in both analogue and digital functions. None of the radical alternative hardware ideas is anywhere near ready to take over. Much more attention will be paid to architecture, and software will be rewritten with much greater attention to the large but finite amount of memory available (as indeed was the case in the 1960s.).

Q1

Knudsen effusion cells with Si, Al, Ga, As ....





$AsH_3 + H_2$

$Ga(CH_3)_3$
$Al(CH_3)_3$ etc.

Q2

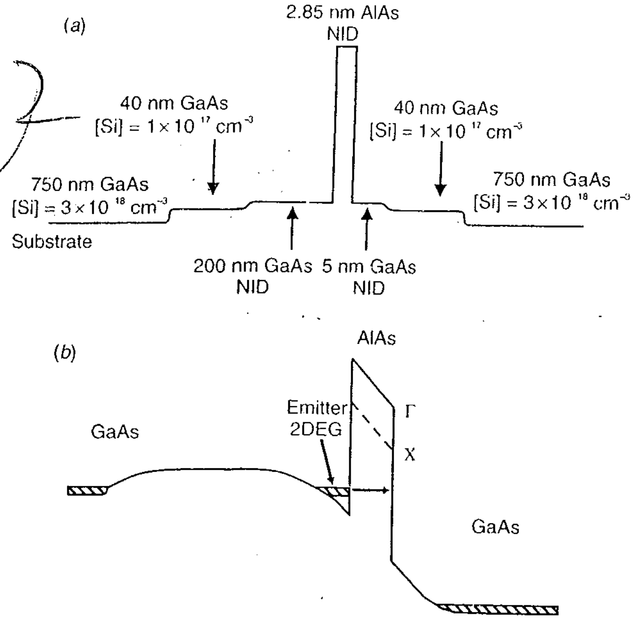


Figure 1. The conduction band profile of the diode (*a*) in the absence of an applied bias, (the doping densities and thicknesses of the epitaxial layers are also shown) and (*b*) under forward bias.

Q3

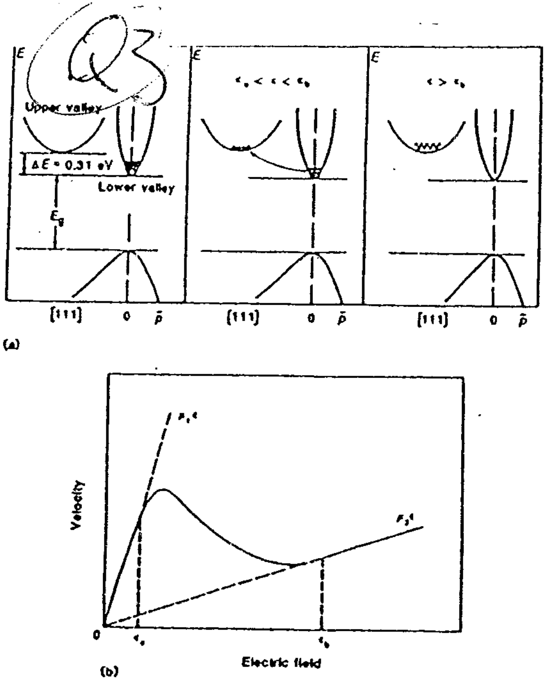
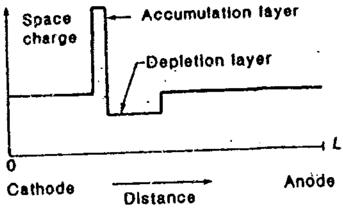
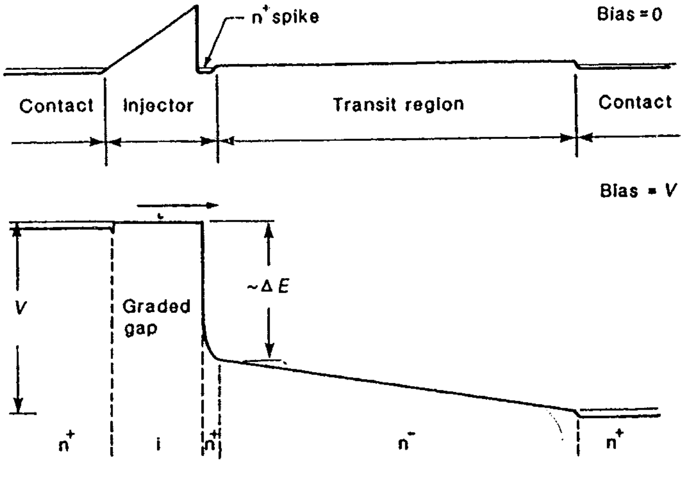


Fig. 1.12 (a) The two-valley origin of negative differential mobility (velocity) in GaAs, showing the increasing transfer of electrons to high-mass low-mobility satellite valleys with increasing field; (b) the resulting velocity–field characteristic. (After Sze © 1981 Reprinted with permission of John Wiley and Sons Inc.).





(a)

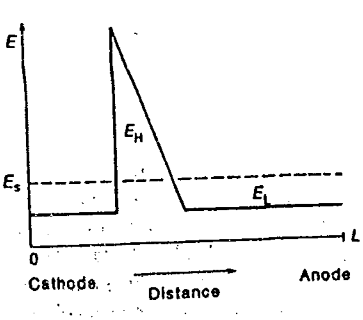
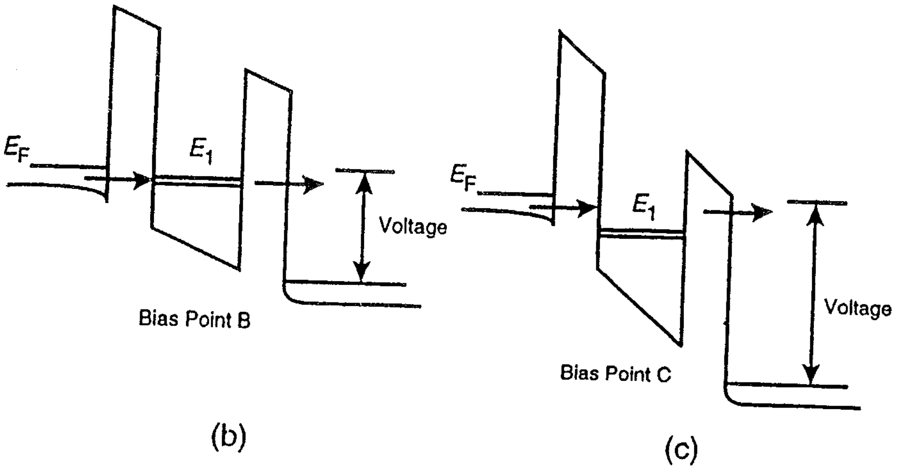


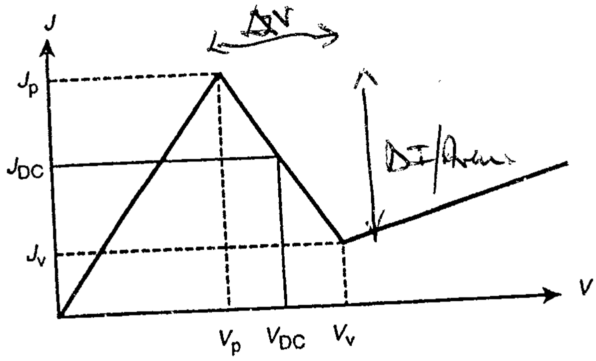
Fig. 17.6 (a) The conduction band profile through a heterojunction cathode Gunn diode at zero bias and strong forward bias, with the latter showing approximately a flat band in the graded-gap region, but a more modest field in the transit region; (b) the current–voltage characteristics of the standard and graded-gap Gunn diode structures (*GEC Plessey Semiconductors microwave products handbook* 1994.)

Q4

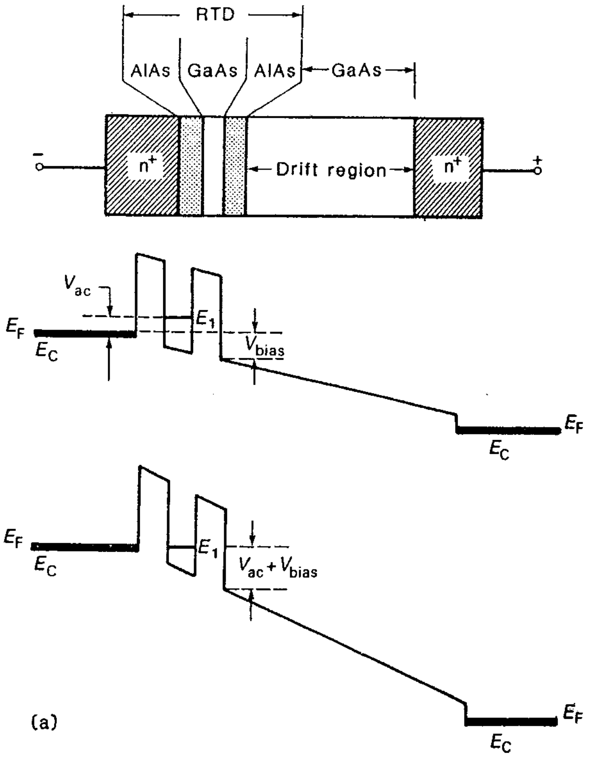


(b) (c)

Fig. 18 (a)–(c) Bias-dependent band diagrams at three bias points A, B, and C. (d) Current–voltage characteristic for a GaAs/AlAs double heterobarrier structure.



Linearized current–voltage characteristic of a resonant-tunneling diode.



Examiner's comments:

Unlike previous years there was a widespread use of the questions (with Q1, Q3 and Q5 being equally popular with Q2 and Q4 slightly less popular) and there was no particular question that stood out as hard or easy, although the marks for Q4 were lower than the others.

Q1 was about the methods of growth and characterization of semiconductor multilayers, finishing with a question on the comparative properties and applications of GaAs and GaN. Q2 was about the asymmetric space layer tunnel diode, as a microwave detector as yet incapable of low cost manufacture. Q3 was about Gunn diode sources, along with the role of heterojunctions to improve performance. Q4 was about conditions in the I-V characteristics needed for microwave sources and detector, how the layers of a double barrier resonant tunneling diode are chosen to optimize output power, and the role of a transit regionat the anode to improve output power. Q5 asked about the advantages of heterojunctions in heterojunction bipolar transistors, and the role and future of Moore's law in driving silicon microelectronics.

Because nearly all the material was new and developed on top of earlier semiconductors courses, the questions were mainly of a bookwork type to elicit the extent to which the candidates had unserstood the general principles of operation and the applications of the advanced electronic devices. The more able students were able to appreciate the finer nuances of the material and to make cross-connections between different parts of the course, which the examination questions encouraged.

As in previous years this course was taken by those candidates with an interest in the hardware aspects of electronic engineering.

One noticeable feature was that, in the absence of an explicit request, candidates tended not to use diagrams in favour of longer sentences which often betrayed less than perfect understanding. In this subject a well-annotated diagram is an easier way to get high marks than a discursive essay making the same points.