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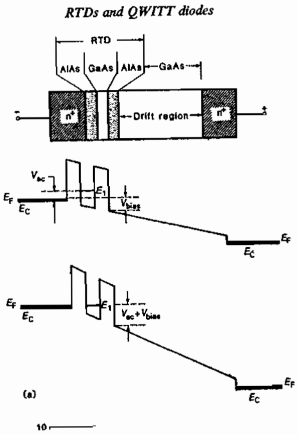
ADVANCED ELECTRONIC DEVICES B18
Exam for 2006 **MODEL ANSWERS**

Q1
(a) Sketch a resonant tunnelling diode (TRD) suitable for DC I-V measurements, showing the multilayer structure and the contacts. Indicate on the diagram, for a GaAs/AlAs RTD, the typical thicknesses and doping levels of all the semiconductor layers in the completed device.

[20%]



(b) Describe, in detail, the processing steps required to produce RTDs from a substrate on which the semiconductor multilayers have been grown. Discuss the mountings required to undertake measurements at 100GHz.

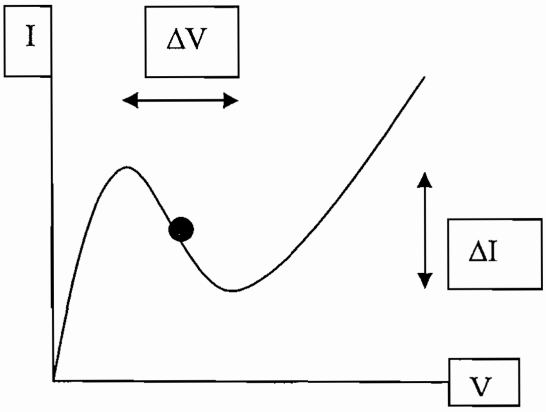
[20%]

Spin coat a resist onto the top of the wafer and bake.
Using a mask set with metal patterns protecting the full diameter of the mesa, expose the resist and wash away.
Etch the mesa to a depth that enters the lower highly doped contact region.
Coat with resist again, and pattern to open up the areas for the contact metallization both on top of the mesa and in a ring around the mesa.
Deposit Ge layer for high doping, Ni for contacting and Au for bonding
Lift off resist to remove excess metal.
Alloy in the ohmic contacts
Dice and bond
(Note of n+ substrate is used, the back surface of the wafer can be used.)

(c) What is the key feature of the DC I-V characteristics that is exploited to generate 100GHz oscillations. How are figures of merit such as the output power and the efficient of the RTD as a detector related to this feature?

[20%]

Negative differential resistance. Peak to valley current ratio and valley to peak voltage ration are the key figures of merit in the DC I-V characteristics.



● Bias Point Io Vo

Output power

Pout = (3/16) ΔVΔI

Efficiency=Pout/(IoVo)

(d) What variations to the multilayer structure described in (a) above could be used to enhance the output power at (say) 50GHz, and why this power is enhanced as a result of your variations.

[20%]

(i) In forward bias increase the doping in the emitter, also make the barriers thinner and use GaInAs in the well layer between the two barriers: these together enhance the ΔI.
(ii) Insert an undoped layer on the collector side of thickness of order 1000nm (about 8-10 time the thickness of the device) to act as a lever arm so that a greater voltage is dropped across the device and so this enhances the ΔV. It is possible to get a few tens of mW at 50% efficiency at 50 GHz.

(e) Discuss the issues relevant to the low-cost manufacture of RTDs.

[20%]c

The control over the layer thicknesses has to be accurate to submonolayer coverage to get adequate reproducibility of devices between wafers and uniformity across a layer. IN spite of much effort, this has not been achieved.

Q2

(a) What is the basic feature of the DC I-V characteristics of a semiconductor diode that enables it to be used as a detector and/or mixer of microwave radiation? Explain why.

[20%]

Curvature in the I-V characteristics, as close to the origin as possible. (Diagram)
Linear I-V characteristics do not allow frequencies to be mixed.
Expand I-V characteristics about a bias point Io, Vo as a Taylor series.

$$I = Io + \alpha(V-V0) + \beta(V-Vo)^2/2$$

Now input a signal $V-Vo=A\sin(2\pi ft)$
Then $\Delta I = \alpha A\sin(2\pi ft) + \beta(A\sin 2\pi ft)^2/2$
If f is a high frequency then averaging over several frequencies the sin term averages to zero but the $\sin^2$ averages to 0.5 so that

$$\Delta I = \beta A^2/4$$

The extra current is proportional to the input power of the signal with β as the figure of merit.

A similar analysis follows if the input signal is a mixture of two frequencies, f and g. The output current will have terms with frequencies f+g, f-g, 2f, 2g etc, all with a proportionality term β.

The DC Power consumed is IoVo, and so it is important nto have these as small as possible, i.e. have the curvature near the origin of ther I-V characteristics. Ideally, if Vo=0, then the detector will operate at zero bias and not consume power.

(b) Describe the semiconductor multilayer structures and the contact metallisation of **three** different realisations of a diode detector of (say) 50GHz radiation: indicate the thickness, composition and doping level of the various layers, and the basis of operation as a detector.

Three of the Schottky diode, the planar-doped-barrier diode, the germanium backward diode and the ASPAT diode. Diagrams needed for each oen, with layer thicknesses etc.
Schottky: a metal-semiconductor contact: curvature at the Schottky barrier height, typically at 0.5-1.0V.
PDB diode an n+ - i – p++ - i – n+ multilayer structure, with a thin p++ layer which fully depletes presenting a negative charge sheet, and hence a potential barrier to further electron transport through the device. The doping thickness product determines the barrier height and the asymmetry in the thickness of the two i-regions determines the asymmetry of the I-V.
Germanium backward diode is just an Esaki diode, an n++/p++ junction, operating in reverse bias. The current mechanism is tunnelling between hole bands and conduction bands. This device operates near zero bias, and is extremely temperature independent.
The ASPAT diode is the same as the PDB except that the p++ layer is replaced by a thin AlAs tunnelling barrier, typically 2.8nm thick. This is also temperature independent.

[30%]

(c) What are the desirable properties of a microwave detector over and above the basic detection function you describe in part (a)? Compare and contrast the performance of each of the three examples.

[25%]

Basic detectivity: Ge backward less efficient than the other three which are comparable
Added nose: tunnelling quieter and ASPAT quieter than Ge Backward
Dynamic range: Ge backward has limited dynamic range, but the others are comparable
Temperature dependence: Ge very stable because tunnelling is nit sensitive to temperature, ASPAT also, but has some thermionic current over the barrier. PDB has thermionic current, but barrier increases with temperature to limit the effect, which Schoittky is all thermionic and is very T-sensitive.
Power consumed in idle mode: again comes back to zero bais which si possible in all except the Schottky
Frequency capability: Schottky can dtectot to THZ, but the thickness of the device for ASPAT and PDB limits to 100-1200GHz.

(d) Describe particular applications for which each of the three diode detectors are particularly suited.

[25%]

Schottky – very high frequency applications
PDB – most tailorable detector I-V, so where systems considerations of applications make specific demands on I-V, then PDB
Ge Backword: where temperature insensitivity is vital
ASPAT – not manufacturable yet, but capable of displacing the other three in pple.

Q3

(a) Describe the operation of a Gunn diode as a source of 30GHz microwaves.

[25%]

Gunn diode: n+ - n- - n+ in GaAs. Place bias across the n- region -8. At high enough field, (3kV/cm), hot electrons transfer from central low mass, low scattering (i.e. high mobility) valley, to high mass, high scattering (i.e. low mobility) satellite valleys in the conduction band. For higher biases, a lower currnet results, i.e. negative differential resistance.
The actual current also breaks up into spikes as the slower electron in the satellite valley are ugmented by electrons from the low mass velley as they scatter and the peak of just transferred electrons grows as it transits the n- region, resulting in a current spike at thr anode. The uniform field is restore, but the accumulation starts as newly accelerated injected electrons transfer after a certain distance (the deadzone) along the n- layer. The resulting sharp peaks in current mean that the output power comes in many harmonics, and there are variations on the design to get either fundamental mode or second harmonic operation as the primary output. The frequency is set by the transit length (n-) of the device, and ranges from several microns down to about 1.6 microns

when set for 45GHz fundamental or 90GHz second harmonic operation. Typical powers are tenths of a watt at 35 and 60GHz and up to 0.1W at 84GHz.

(b) Discuss the performance limitations in of such a diode that could be circumvented by the introduction of semiconductor heterojunctions into the design.

[25%]

The process of heating to the 0.33V needed for electrons to transfer to the satellite valley is such that electrons can loose this energy many times over by a parallel process of optical phonon emission. This means that only some of the electrons transfer, reducing the efficiency of the device. The electron-phonon scattering process is very temperature dependent, and this means that the performance of the device is also very temperature dependent. The transfer is stochastic and this adds to the noise of the device.
By introducing a ramp of AlGaAs with Al concentration rising from 0% to 30% over about 50nm, the electrons can remain locally cold as they are heated with respect to the conduction band minimum in GaAs. The electrons when crossing the heterojunction back to GaAs can transfer immediately before much phonon loss has occurred. This improves the efficiency of the device, reduces the noise and greatly reduces the temperature dependence. In addition the 'dead layer' can be eliminated and the shorter transit region allows for higher fundamental mode operation from frequencies of just over 60GHz to as high as 94GHz.

(c) Describe, both qualitatively and quantitatively, the actual improvements when heterojunction elements are introduced electrons into a GaAs Gunn diode.

[25%]

In the range 35-100GHz, the heterojunction efficiency, and so the output power, double.
The single side-band noise is reduced by a factor of 10
The temperature dependence of the output between -40C and 100C reduces from a factor of 300% to about 30%.

(d) Compare and contrast the performance of a Gunn diode and an IMPATT diode as the source of radiation in the range from 30GHz to 100GHz.

[25%]

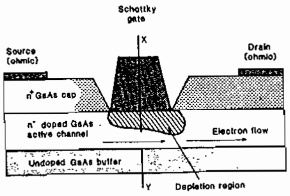
The IMPATT diode can deliver of order 30W in the range to 100GHz, to be contrasted with the 0.1W from a Gunn diode. The IMPATT diode is a much noisier device and less suited for delicate RADAR applications.

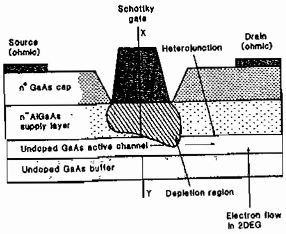
Q4

(a) Sketch, with details of layer thicknesses, compositions and doping levels, typical homojunction and heterojunction versions of field effect transistors and bipolar transistors based on GaAs.

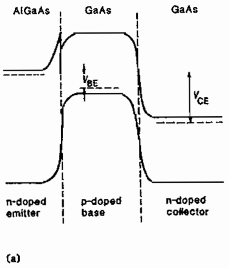
[50%]

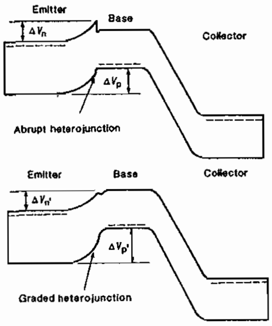
Textbook diagrams of devices, typified by those given.



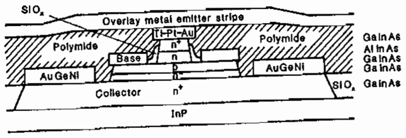


Heterojunction bipolar transistors





Layer	Composition	Doping n (cm^{-3})	Thickness (μm)
Contact	GaInAs	$n = 1 \times 10^{19}$	0.15
Emitter	AlInAs	$n = 1 \times 10^{19}$	0.1
Emitter	AlInAs	$n = 5 \times 10^{17}$	0.15
Spacer	GaInAs	$n = 5 \times 10^{17}$	0.02
Base	GaInAs	$p = 5 \times 10^{19}$	0.15
Collector	GaInAs	$n = 1 \times 10^{16}$	0.6
Subcollector	GaInAs	$n = 1 \times 10^{19}$	0.7
Substrate	InP	Semi-insulating	



(b) Describe the advantages in the performance of these two transistor types with the introduction of heterojunctions.

[50%]

Heterojunctions in III-V semiconductors are pervasive.

FETs:

- (i) Higher frequencies for the same lithography from lower access resistance with HJs,
- (ii) Much higher resistances overall – circuits at 100GHz.
- (iii) Much noise over and above reduction in resistances for reasons not clear
- (iv) Higher power applications possible with higher 2D electron densities and high current levels

HBTs

- (i) higher base doping possible without reverse injection form base to emitter
- (ii) lower base resistance implies higher frequencies
- (iii) wider temperature range of operation
- (iv) greater power operation without current crowding and base punch through
- (v) lower noise
- (vi)

Q5

(a) The following mulilayer semiconductor structure is the specification for a frequency multiplier.

Substrate:	GaAs	Si-doped at 10^{18}cm^{-3}.
On this is grown;		
Layer 1 (buffer)	GaAs	Si-doped to 10^{18}cm^{-3}, to a thickness of 0.5μm.
Layer 2	GaAs	not intentionally doped, to a thickness of 0.2μm
Layer 3	AlAs	not intentionally doped, to a thickness of 2.8nm
Layer 4	GaAs	not intentionally doped, to a thickness of 0.2μm
Layer 5 (contact)	GaAs	Si-doped to 10^{18}cm^{-3}, to a thickness of 0.5μm.

Describe in detail, the ways this multilayer structure might be grown in practice, and point to the advantages that either molecular beam epitaxy or metal-organic-chemical vapour deposition have in the growth of this structure.

[40%]

This is the same as the ASPAT diode where the tunnel barrier is in the middle of the nominally undoped region, leading to a nonlinear but antisymmetric I-V characteristic.

Issues:

The thickness of layer 3 is critical in setting the level of the current obtained, as this is exponentially sensitive to the height of the barrier (that is pure AlAs rather than an alloy with high Al concentration), and the thickness, which must be correct to within +/-0.2 of a monolayer – difficult but possible.

Control over layers 2 and 4: these must be closely equal in thickness, even if they are not exactly the specified length. It is important to keep the doping as low as possible and residual n-type.

MBE has better in-situ diagnostics to check on the layers during growth than MOCVD. MBE tends to give layers thicker than the target, but MOCVD tend to be thinner, and this latter is more useful here.

(b) Describe in detail, two techniques that might be used to verify the thicknesses of the above layers, and layer 3 in particular. Describe in detail two techniques that might be used to verify the doping of the GaAs layers.

[40%]

Layer thicknesses:

X-rays: How, why, interpretation, difficulty with layer 3, non-destructive and capable of wafer mapping….

TEM: Expensive, time-consuming, gives data at isolated points, destructive, but capable of getting towards the precision needed to get the AlAs layers. New research is such that

the doping profile might show up in scattering off the heavily doped and nominally undoped layers.
SIMS: Expensive, time-consuming, gives data at isolated points, destructive, but can give the composition and thicknesses and doping of the various levels in one go.

Doping:
Hall – for the contact layers only
Photoluminescence, IR and other optical techniques, again for the contact layers.
A bevelled edge may be used with optical techniques to get a crude estimate of the total thicknesses of layers 2-4 includise.

(c) Discuss the issues of manufacturability of this device for a proposed application in low-cost, high-volume systems.

[30%]

Similar to the ASPAT _ real problem being the precise control over layer 3, which is not achieved yet.