PART IIB 2011 4B18 ADVANCED ELECTRONIC DEVICES PROF M J KELLY

Engineering Tripos Part IIB 2011- Module 4B18 - CRIB

1 (a) MBE and MOCVD – standard figure with dimensions (1m versus 30nm), UHV versus low pressure, stainless steel versus glass, one monolayer per second versus 10 monolayers per second, evaporation of atomic species versus cracking of precursor molecules, safety more of an issue with MOCVD, higher throughput for MOCVD, MBE popular for microwave devices, MOCVD for optical devices, both cost of order £1M, better in-situ control and monitoring for MBE versus MOCVD, ...

(b) Layer 3 is a tunnel barrier, and it requires TEM to confirm the thickness and atomic composition, and detailed modelling of the defocused bright field images is required to extract the precise potential profile for electrons that is represented by the AlAs layer. The depth of this layer from the top surface can be checked by X-ray analysis or SIMS as well as TEM. The contact layer could be verified by SIMS or be CV profiling.

TEM can specify to within about 0.1 nm at best for the tunnel barrier layer (3), and to 1-10 nm from X-ray or SIMS. This also applies to the thickness of the contact layer by SIMS, with CV profiling being at the 10nm level.

2 (a) Gunn diode domain formation: n+ - n- - n+ placed under strong bias. Electrons heat up in the n- region from the cathode, and eventually they transfer to the satellite conduction band of heavier effective mass, where they have a slower velocity as well. This means that an ever-widening drop in electron density propagates forward ahead of a thin layer of higher electron density of the slower satellite electrons, propagating at the saturated drift velocity of the transferred electrons. This spike of electrons eventually reaches the anode and the process begins again. The net result is an output current that is a thin spike of current which has very many high harmonics in the output. [Standard diagram of all this.] 0.5W at 35 GHz, 0.05 W at 90 GHz (2nd harmonic), 300% change in output power over the -20 to +100C range....

(b) The reduction of the bias to just below threshold of a part of the ac cycle allows a wider pulse to be obtained and more energy in the fundamental mode. [Delayed domain mode, standard diagram].

(c) Heterojunction allows electrons to be cold as they cross the graded layer but suddenly become 0.3 eV hot as they cross the heterojunction, and are then capable of immediate transfer to the satellite valleys. Result: doubling efficiency over the 30-100 GHz range, double output power over the range, fundamental operation up to 80+GHz from 60-GHz in GaAs, 90% reduction in single sideband noise, temperature dependence of output power reduced by factor of nearly 10 over the -30C to +80C range. Less frequency pulling as a function of bias. All explainable in terms of the nature of the suddenness of the heating of the electrons at the heterojunction.

3 (a) The multilayer structure is symmetric and the I-V characteristic is both anti-symmetric and non-linear. It is used as a frequency multiplier to give odd (only) harmonics.

(b) The asymmetric version is the ASPAT (asymmetric spacer layer tunnel) diode used as a mixer or detector. It works on the basis of tunnelling (contrast thermionic emission for the Schottky barrier or the planar-doped-barrier diodes), and has cool electrons with very low 1/f noise and noise floor. It has the same dynamic range as a Schottky, but a lower upper frequency (200 GHz instead of 2 Tz because of the thicker transit layer). It has a very low temperature dependence (no thermionic emission), and this will be its main advantage over the others.

(c) The critical layer is the tunnel barrier (layer 3), which is exponentially sensitive to the layer thickness with a factor of 3 fall in tunnelling probability for every extra monolayer of AlAs in the barrier. For achieving I-V reproducibility wafer-to-wafer at the 20% level, the barriers have to be the same within 0.1 monolayer and that has proved impossible to date. Hence this and other tunnel devices have not had the reproducibility needed for low cost, high volume production that would allow pick and place manufacture. If every device has to be picked and tested first before placing if OK, the cost goes up by a factor of 10 in the overall system manufacture.

4 (a) Take the gate-length- cut-off frequency diagram for Si, GaAs, GaAs/AlGaAs and InGaAs/InAlAs and the improved mobility and carrier densities to show monotonic increase in the L_gXf_t product. Noise in HEMTs devices much lower – no carrier-ion scattering.

(b) Wider-gap emitter leads to (i) higher injection efficiency from emitter, (ii) higher base doping, (iii) lower base resistance, (iv) less current crowding at perimeter, and wider temperature range of operation. All realised, without extra complications in processing, so that HBTs are now ubiquitous in III-Vs.

(c) T-gate – made with two layers of resist exposed to different widths, used as gate for high-frequency transistors, to be able to have low resistance but shorter footprint on the semiconductor.

5 (a) Johnson criteria: Two Johnson equations: $V_m f_T = (E_B v_s)/2\pi$ and $PZ(f_T)^2 = (E_B v_s)^2/32\pi^2$

Proof is a simple text-book exercise given in the lecture notes.

E_B for GaN is 3.3 time that of GaAs: v_s for GaN is 1.5 times that of GaAs so $(E_B v_s)_{GaN}/ (E_B v_s)_{GaAs} = 5$

Can get five times bias for same frequency, or 25 times as much power at same frequency.

(b) Strain in the Si/Si-Ge system was a major barrier to early applications, more recent understanding has been able to overcome many aspects of strain. The band-gap offsets are much smaller, and more complex in the Si system than in the III-V system, mainly because of the multiple degeneracies of the Si conduction band which are partly lifted by strain.

Examiner's comments:

Q1: Materials growth and multilayer qualificatons
Q2: The heterojunction Gunn diode
Q3: Tunnel devices
Q4: Microwave transistors
Q5: Johnson criteria and heterojunctions in silicon

The students had mostly grasped the basic points in the questions, but I was surprised this year just how many students chose not to use diagrams, where this would have been much more efficient and effective.

In addition this year I noticed a wider spread of marks between questions answered by the same candidate than was the case in earlier years.

That said there were four very strong candidates.

In Q2(b) and Q4(c), the students had to have picked up points of detail that were clearly in the notes, and the latter emphasised in the lectures, but few did these parts well, and some misunderstood the basics.

Some chose not to answer the question as specifically posed, but to write down everything relevant they could think of.

Only a few read the question closely and answered it in the detailed way in which the question was asked, e.g. giving quantitative figures of merit, or quantitative feature sizes, where these had been explicitly asked for.