EEE6042 ANSWERS 2007-2008

1(a) The seven crystal systems are:

Cubic -

Tetragonal

Hexagonal

Trigonal

Orthorhombic

Monoclinic

Triclinic

1(b) Consider a *unit cell* in the diamond cubic lattice

Xthe unit cell is a cube - 90E internal corners and equal length edges Xthe cell edge length a₀ - the *lattice parameter*

Miller indices relate to an x,y,z, coordinate system along the edges of the unit cell

A plane intersects these coordinates at three points: p(x), q(y) and r(z)

The Miller indices of the plane are h=1/p, k=1/q and l=1/r

Xh,k and I must be multiplied up to integers

1(c) Plane spacing
$$d_{hkl} = a_0 / \sqrt{(h^2 + k^2 + l^2)}$$

For (110)
$$d_{220} = 0.5325 / \sqrt{(1+1+0)} \text{nm}$$
$$= 0.3765 \text{nm}$$

For (111)
$$d_{310} = 0.5325/\sqrt{(1+1+1)}$$
$$= 0.3074 \text{nm}$$

For (113)
$$d_{311} = 0.5325 / \sqrt{(1+1+9)}$$
$$= 0.1606 nm$$

For (422)
$$d_{422} = 0.5325 / \sqrt{(16 + 4 + 4)}$$
$$= 0.1087 \text{nm}$$

- 1(d) (113) is perpendicular to (12-1)
 - (114) is perpendicular to (1-10)
 - (114) is not perpendicular to (0-10)
- 1(e) <For Si, Group V impurities (P, As, Sb) have an extra outer electron and they readily give this up to the Si lattice

Xthese impurities are donors

Xthey introduce *shallow states* into the energy gap just below the conduction band (Fig required)

Bthe ionisation energy is <kT so that all will be ionised Bmany electrons introduced into the conduction band Bthe Si becomes *n-type* <For Si, Group III impurities (B, Al, Ga) have one too few outer electrons and they readily accept an electron from the Si lattice

Xthese impurities are acceptors

Xthey introduce *shallow states* into the energy gap just above the valence band (Fig required)

Bthe ionisation energy is <kT so that all will be ionised Bmany holes are introduced into the valence band Bthe Si becomes *p-type*

1(f) Lattice diagram and explanation of a Burgers circuit required.

Perfect dislocation a/2[110] type Frank partial dislocation a/3[111] type Shockley partial dislocation a/6[112] type

2(a) Metal-Organic CVD (MOCVD)

<layer growth takes place inside a *reactor tube* often made of quartz glass
Bsubstrate sits on a heated graphite susceptor
Bheating is by coupling of susceptor with RF
coils may be asymmetrical to give uniformly heated zone

< Hydrogen high purity carrier gas passes through the reactor, transporting the reagent gases which it contains over the substrate</p>

Xflows of all gases and appropriate mixing is regulated by mass-flow controllers in a gas switching matrix

Bvent/run operation with zero differential pressure changes

Xafter initial in situ cleaning of the substrate by heating in flowing gas (with eg AsH_3 for GaAs), layer growth takes place at either atmospheric pressure or low pressure (perhaps approx 150torr)

Xreagent materials pyrolyse on the heated substrate to provide the epitaxial growth Xwaste products from the reactor pass through various stages of processing, such that there are zero toxic emissions

<Properties required of reagent materials (precursors)</p>

Xshould have *high volatility*

Bmakes possible high layer growth rates

Xshould have a low tendency to decompose homogeneously

Bonly decomposes heterogeneously on substrate

Xshould *eliminate carbon* as completely as possible when cracking upon the substrate surface

Bavoids problem of carbon doping of grown material

Xshould be available with very high purity

Botherwise unwanted impurities can be incorporated into a growing layer

< Group III precursors

Xmost useful are trimethylaluminium

trimethylgallium trimethylindium

< Group V precursors

Xmost useful are: arsine (AsH₃)

phosphine (PH₃)

Bthe former is highly toxic and the latter is both toxic and pyrophoric

<Dopant precursors

Xthe most general p-type dopant in III-Vs is $\mathbf{Z}n$: introduced as dimethylzinc

Bin Al-containing compounds, C dopant can be used: introduced as CCl₄

Bin GaN, only Mg is satisfactory: introduced as methylcyclopentadienlymagnesium

Xthe most general n-type dopant in III-Vs is Si: introduced as SiH₄ or Si₂H₆

<The *MOCVD growth process* involves interaction between the group III and group V species on the heated substrate surface after they have diffused across a stagnant gas boundary layer

Xfor the growth of GaAs:

 $Ga(CH_3)_3 + AsH_3 6 GaAs + 3CH_48$

Xthe group V precursor is typically *present in excess* to compensate the high volatility of the element and to inhibit carbon incorporation

XMOCVD growth characteristics

Bgrowth rate is *controlled* by the group III precursor concentration

Bgrowth rate is *little affected* by the group V precursor concentration

Bgrowth rate depends upon the temperature in three regimes

increase at low temperatures due to speeding up of reaction kinetics intermediate regime limited by diffusion across boundary layer decrease at high temperatures due to desorption of group V element

2(b) Diagrams of compressive and tensile pseudomorphic layers required.

<When the lattice parameters of the deposited layer and the underlying crystal cannot be accurately matched, the interface is then *lattice mismatched*

<If the lattice mismatch is relatively *small* (<1.5%), the growing layer can first adopt the in-plane lattice parameter of the crystal substrate

Xhowever, the small difference in lattice parameter results in a *tetragonal distortion* of the unit cells in the growing layer

Bif the growing layer is compressed in-plane, the lattice constant normal to the plane increases slightly

Bif the growing layer is stretched in-plane, the lattice constant normal to the plane decreases slightly

Xsuch epitaxial layers are described as *pseudomorphi*c

<Pseudomorphic layers can be grown only up to a certain thickness, due to the increasing excess energy stored in the distorted lattice</p>

Xabove this *critical thickness*, defects are introduced into the layer

Bthese are often *dislocations* which may glide into the heterointerface to relieve the misfit and induce *relaxation*

with a certain density of dislocations at the interface, the deposited layer can return to its equilibrium cubic lattice geometry

Xfor layers above the critical thickness dislocations can be introduced into the heterointerface by a number of different mechanisms

Bpre-existing threading dislocations are forced to bend over into the interface, whereupon they extend across the layer

the edge components of the Burgers vectors in the interface relax the strain - *Matthews and Blakeslee mechanism*

Bif there are any inhomogeneities in the layer (precipitates, etc), local strain can produce dislocation loops which expand into the interface

so-called secondary sources

<If the lattice mismatch is relatively *large* (>1.5%), the sign of the lattice distortion determines the outcome

Xif the grown layer is under *tension*, it is likely to behave simply as already described

Xif the grown layer is under *compression*, it will become morphologically distorted Bas layer growth proceeds, after a small number of uniform monolayers, there is often a transition to the growth of isolated, small islands (a *Stranski*-

Krastanow transition)

islands can be exploited as *quantum dots* in eg laser cavities

Bfurther growth leads to island overlap and the formation of undulating, *wavy continuous layers*

islands and undulations are produced because *lateral dilatation* of the lattice in the growth crests (which are unconstrained) lowers the strain energy of the system

Bultimately, for sufficiently thick grown layers, arrays of misfit-relieving dislocations will be introduced

3(a) Ion implantation is employed because it offers *advantages* over simple dopant diffusion into a semiconductor: in particular it gives

Xvery accurately controlled doping concentrations

Xtightly controlled depth distributions

Xhigh reproducibility

Ion Implantation Apparatus

<The dopant is initially produced in the form of a gas (from a cylinder) or a vapour (from a heated solid or liquid)

Xthe gas or vapour is ionised by an electron beam to give *positive ions*

<The ions are extracted at relatively low energy from the *ion source* and pass into a high vacuum between the poles of a *bending magnet*

Xthis provides *mass analysis* for eg isotope separation

<Ions of the selected mass emerge through a resolving aperture and are *accelerated* further to the desired energy

<The ion beam is often *scanned* by electrostatic plates over the wafer to be implanted. Xthe implant is made *homogeneous* by the rastering of the beam.

Xthe ion dose can be *calibrated* by use of a Faraday cage monitor

Xwafers are typically held on a carrousel or loaded individually from cassettes

Xsome implanters mechanically scan the wafers in front of the ion beam

Behaviour of Implanted Ions Within the Semiconductor

<An ion passing through a solid undergoes *collisions with electrons and atomic nuclei* Xit progressively loses energy, typically at 5-100eV/nm

Bdepends on mass and energy of ion and on the substrate

Xnuclear collision losses dominate at low ion energies, while electronic collision losses dominate at high ion energies

Bthe cross-over point between the two types of process depends upon the ion mass: it moves to lower energy for light ions and to higher energy for heavy ions

heavy ions produce more nuclear collisions

Xnuclear collisions at high energy displace semiconductor lattice atoms giving *lattice damage*

Bthe secondary displaced atoms can produce additional damage in the lattice by displacing further atoms giving a *cascade of atomic collisions*

<The *crystallographic orientation* of the substrate affects the rate of ion scattering considerably

Xions incident along a low index crystallographic direction *channel* down the lattice holes making *correlated glancing collisions*

Bthey penetrate larger distances by such channelling

Xions not incident along a discernable crystallographic direction (ie incident along a *random direction*) do not channel and lose energy more rapidly

Bthey penetrate shorter distances

3(b) <The substrate lattice damage produced by implanted ions consists largely of interstitials and vacancies, complexes of these defects (point defect clusters) and amorphous zones depending upon the mass and dose of ions implanted

Xlow to moderate doses (say 10¹³ - 10¹⁵/cm²) of *light ions* such as B⁺ in Si produce dispersed damage ranging up to *buried bands of point defect clusters*

Xhigh doses (say 10^{15} - $>10^{16}$ /cm²) of *heavy ions* such as Sb⁺ in Si give *continuous amorphous layers* to the substrate surface due to overlap of individual amorphous zones produced by each implanted ion

Implanted Layer Annealing

<In order to achieve electrical activity of implanted dopants, it is necessary to substantially remove the lattice damage introduced during implantation

Xas-implanted layers generally exhibit *very high resisivity* due to the presence of carrier traps and recombination centres of defect origin

<Annealing of implanted layers at high temperature in a furnace can satisfactorily achieve this goal and can leave dopant atoms on electrically-active substitutional sites</p>

Xhowever, for given annealing conditions, the rate of recovery of the lattice and the concentration of residual defects depends upon the nature of the initial damaged layer

Bif the initial damage is in the form of a *point defect cluster band* (due eg to B⁺ ion implantation in Si) this usually evolves into *tangled dislocation loops* which can only be removed at very high temperatures (900-1000EC)

Bif the initial damage is in the form of a *continuous amorphous layer* (due eg to Sb⁺ ion implantation in Si) this will generally regrow from the amorphous/crystal interface to give *defect-free epitaxial single crystal* Si at relatively low temperatures (500-600EC)

Xinitial amorphous layers generally offer better dopant activation at lower temperatures due to the relatively perfect lattice regrowth

3(c) i) regrowth velocity =
$$v_0[\exp(-E_A/kT)]$$

= $3.68 \times 10^8 [\exp(-2.76/8.61 \times 10^{-5} \times 923)]$
= $3.68 \times 10^8 [\exp(-34.73)]$
= $3.039 \times 10^{-7} \text{cm/s}$

ii) time required to regrow 1.5x10⁻⁵cm:

=49s

$$= 1.5 \times 10^{-5} / 3.039 \times 10^{-7} s$$

4(a) < Complimentary MOS (CMOS) transistors

Bthe overwhelmingly dominant technology for microprocessors and memory

previously used NMOS technology has been displaced due to greatly reduced power consumption, enhanced soft (α -particle-induced) error immunity and other features offered by CMOS circuits

<Bipolar transistors

Bvery high speed logic circuit and RF applications in eg the telecoms area

offer higher switching speeds than MOS transistors but occupy larger Si area and consume more power (combined technology - BICMOS - is available)

4(b) <The process employs a p-substrate for the n-channel devices and n-wells are formed for the p-channel devices (the example here shows the fabrication of a pair of such devices). Positive photoresist is used throughout

X(a) N-well implant and drive-in

Bthe starting wafer (p-type, 17-34 Ω cm, (001)) is oxidized and a window opened using photolithography and etching. The ion implant is 3 x 10^{12} /cm² at 80keV and is driven in at 1150EC to a depth of -2μ m

X(b) Oxide/Nitride masking layers for LOCOS

Blocal oxidation of Si (LOCOS) involves the growth of a thick oxide layer and is necessary for isolation between devices. Masking against oxidation uses deposited nitride (160nm) on a grown pad oxide (40nm)

X(c) Oxide/Nitride patterning

Bplasma etching (CHF₃) is used for window etching

X(d) Field threshold adjust implant

Ba resist mask is used to define a B⁺ ion implant in the window areas this is needed to raise the threshold of parasitic MOS devices, across the field oxide, so that they will not become active during IC operation.

X(e) Field oxide growth (LOCOS)

Bthe oxide is grown to a thickness of $0.8\mu m$. Remaining nitride and oxide are stripped (with orthophosphoric and buffered hydrofluoric acids) and B⁺ ions are implanted into the active areas (-10^{12} cm⁻² at 30 keV) for transistor threshold control

the nitride mask lifts slightly at its edges and oxide grows a little laterally giving the so-called *Bird's Beak* effect

X(f) Gate oxide growth and polySi deposition

Bgate oxide (40nm) is grown in dry oxygen at 950EC with a few % of HCl added. Next, polySi deposition is carried out at 610EC in a LPCVD reactor: the polySi is doped n-type at $-20\Omega/\sim$.

X(g) PolySi patterning and etching

Bthe polySi is protected by photoresist and etched using a chlorine- or bromine-based plasma

X(h) Resist mask and p^+ source and drain implant

Bthe implant $(BF_2^+ 5x10^{15} \text{ cm}^{-2} \text{ at } 50 \text{keV})$ dopes the *self-aligned* p⁺ sources and drains in the n-well and dopes the contact window for the substrate connection.

X(i) Resist mask and n⁺ source and drain implants

Bthe implant (As⁺ 5x10¹⁵ cm⁻² at 80keV) dopes the *self-aligned* n⁺ sources and drains and the contact window for the n-well connection in both (h) and (i), the implantations have to be done slowly enough for the deposited charge to leak away before electrostatic damage occurs

X(j) BPSG deposition and contact window etch

BSiO₂ is deposited by reacting silane and oxygen at 400EC. Diborane and phosphine are incorporated to give borophosphosilicate glass (BPSG), which is reflowed at 1100EC for 10s by RTA. The latter also recrystallizes the damage from the source and drain implants and activates the dopants. Contact windows are finally etched in the BPSG

X(k) Metal deposition and etch

BAl with 1% Si is sputtered onto the wafers to a thickness of 1 μ m. This is protected with photoresist and etched in a chlorine plasma to form the interconnects. The remaining metal is annealed at -450EC in forming gas (H_2/N_2) to form low resistance contacts to the devices

4(c) Diffusion coefficient (D) = $D_0 \exp -[E_A/kT]$

At 1150°C (1423K)
$$D = 12 \text{ x exp} - [4.05/(8.61 \text{ x } 10^{-5} \text{ x } 1423)] \text{ cm}^2/\text{s}$$

 $= 12 \text{ x exp} - [33.06] \text{ cm}^2/\text{s}$
 $= 5.27 \text{ x } 10^{-14} \text{ cm}^2/\text{s}$
For 30min $2\sqrt{(Dt)} = 2\sqrt{(5.27 \text{ x } 10^{-14} \text{ x } 1800)} \text{ cm}$
 $= 1.947 \text{ x } 10^{-5} \text{ cm}$
 $= 0.19 \mu \text{m}$