EEE6070 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 a_0 - 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 l must be multiplied up to integers

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

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

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

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

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

    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)

    X**reagent 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)

    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 (AsH_3)
phosphine (PH_3)
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 ***Zn***: introduced as dimethylzinc
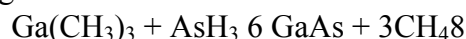Bin Al-containing compounds, ***C*** dopant can be used: introduced as CCl_4
Bin GaN, only ***Mg*** is satisfactory: introduced as methylcyclopentadienlymagnesium
Xthe most general n-type dopant in III-Vs is ***Si***: introduced as SiH_4 or Si_2H_6

<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 ***pseudomorphic***

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

    X*very accurately controlled doping concentrations*

    X*tightly controlled depth distributions*

    X*high 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
    X*nuclear 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*
        B*they 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
        B*they 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 10^{13} - 10^{15}/cm^2) 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}/cm^2) 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*
    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 $1.5 \times 10^{-5}\,\text{cm}$:

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

          $= 49\text{s}$

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, 17-34Ωcm, (001)) is oxidized and a window opened using photolithography and etching. The ion implant is $3 \times 10^{12}/\text{cm}^2$ at 80keV and is driven in at 1150EC to a depth of −2μm
          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 (CHF$_3$) 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 0.8μm. 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 30keV) 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} cm^{-2} at 50keV) 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$^+$ 5x10^{15} 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*

BSiO$_2$ 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 1μm. 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) $D = 12 \times \exp -[4.05/(8.61 \times 10^{-5} \times 1423)] \text{ cm}^2/\text{s}$

$$= 12 \times \exp -[33.06] \text{ cm}^2/\text{s}$$

$$= 5.27 \times 10^{-14} \text{ cm}^2/\text{s}$$

For 30min $2\sqrt{(Dt)} = 2\sqrt{(5.27 \times 10^{-14} \times 1800)} \text{ cm}$

$$= 1.947 \times 10^{-5} \text{ cm}$$

$$= 0.19\mu m$$

5(a) Scanning Tunnelling Microscopy

Electrons *tunnelling* between a sharp tip and a surface give a signal which allows *3D images* of the surface to be produced
   • *spectroscopy* provides information about the *electronic structure* of the sample by probing the density of states as a function of energy

Basic instrument consists of a scanner and a sample-tip approach mechanism
   • *scanners* are made of piezoelectric elements which expand upon application of an electric field
      ° typical configurations are orthogonal bars or a cylindrical arrangement
      ° computer-controlled voltage drive with feed-back stabilisation
   • *tip-approach* controlled by differential springs or levers which have a movement step resolution of better than 3nm
      ° piezo-elements also again used
   • tips often formed from W wire by mechanical grinding or electrochemical etching
      ° finest tips prepared by ion beam machining
      ° less stiff, but oxide-free tips can be made from Au or Pt
   • STMs can operate in air, but vacuum gives better characterised oxide-free surfaces
      ° in UHV, semiconductors can be heated to >1000°C for *in situ* epitaxial growth studies

The mechanism of operation relies upon *tip-surface electron tunnelling*, and this depends upon the electronic structure of the tip, that of the sample and the tunnelling barrier (related to the work-function of the sample) - two *imaging modes*:
   • '*constant current*' imaging where the tip is scanned with a constant separation from the surface atoms
      ° maps constant charge-density contours
   • '*constant height*' imaging where the changing current gives a surface image
   • *resolution*: approximately atomic in all directions

Tunnelling spectroscopy can be performed in two modes:

- '*point spectroscopy*' where tip is moved to a feature of interest and tunnelling current is recorded as a function of tip bias
  - ° magnitude of current at a specific voltage directly related to density of states in the sample at that energy
- '*current imaging spectroscopy*' where images of an area are collected for a number of tip biases
  - ° identifies the spatial position of energy states with respect to the lattice

Many **applications** in determining the structural and electronic characteristics of semiconductor surfaces

- some of the first studies showed the nature of the 7x7 reconstruction of the Si (111) surface
- STM has demonstrated the nature of 'dimer rows' on the Si (100) surface
- the nucleation of epitaxial layers has been studied in detail

Nanolithography: atoms can be moved using the tip
- formation of 'quantum corral' with ring of Fe atoms
  - ° electron charge-density variations visualised within

5(b) **Atomic Force Microscopy**

Basic instrument similar to STM but a constant force is maintained between the tip and the sample
- specimen generally mounted on a *piezostage* which carries out the scanning
- fine tip (often Si_3N_4 or Si) mounted on cantilever tracks across the surface during scan
  - ° force on cantilever measured by *reflected laser beam* and detector
  - ° *force maintained constant* by actuating z-drive of stage: correction signals stored to give image
    - *vertical resolution* typically ~0.2nm

Two main *modes of operation*
- *contact mode*: the tip experiences short-range, repulsive forces produced by the surface atoms
  - ° yields *best surface lateral resolution*: typically 2-5nm-scale but can be atomic-scale on ultra-smooth surfaces with very fine tip
    - on grooved surfaces with steeply-sloping sides tip may not accurately track features: tip shape important
  - ° adhesion forces (due to adsorbed gas layers and electrostatic charges) can lead to *surface damage*
    - operating in 'tapping mode', with resonantly vibrating cantilever, can eliminate adhesion damage and improve resolution
- *non-contact mode*: the tip experiences only long-range, attractive Van der Waals forces produced by the surface atoms

° yields relatively ***poor surface lateral resolution*** due to insensitivity of long-range fields to details of surface structure

° ***adhesion eliminated*** so that surface damage does not occur, although force-balance can be unstable

Applications to surface structure assessment

- wide ranging structure scales: 'atomic structure' (graphite) to large-scale (IC)
- semiconductor surface step arrays
- epitaxial layer morphology

6(a) Structure of the Scanning Microscope

<Electron-optical column, with electromagnetic lenses, maintained under high vacuum
    Xextensive signal handling (processing) and display electronics

<Electron gun similar to that of TEM
    Xtypically W hairpin, LaB_6 or field-emission electron sources
    Xaccelerating voltages up to typically 30-50keV

<Electron beam formed into ***fine spot*** (sometimes down to <2nm) by lens and aperture system
    Xpassed through scan coils to deflect the spot in a raster over specimen held on high-accuracy goniometer stage
    Xincident electrons in the spot interact with the specimen throughout a scattering volume which increases with increasing beam voltage
        BMonte Carlo simulations demonstrate this

<***Signals generated*** by interaction of incident beam with specimen surface regions are principally:
    Xsecondary electrons
        Btypically 0-50eV energy
        Bdetected using eg scintillator/PMT
    Xbackscattered electrons
        Btypically near primary beam energy
        Bdetected using eg solid-state diode
    Xinduced currents
    Xvisible, UV or IR photons
    XX-rays

<Specimen can be imaged or analysed using any of these signals
    Ximage formed on CRT display modulated by signal and scanned in synchronism with the specimen
    Xadvantage of SEM is that specimens usually require little special preparation (ie no thinning as for TEM)
        Belectrical charging may be problem for insulating materials: coating with very thin film of C or Au can overcome this

6(b)i) Electron Emissive Mode

<*Secondary electron (SE) image* shows surface structure and topography, often with excellent visualisation of *3D relief*

    Xvery large *depth of field*: up to 300x that of light optical microscope

        Bdue to relatively *small beam divergence* angle (-10^{-2}-10^{-3} rad)

    Xbright/dark shading in the image gives the *3D appearance*

        Bdue to angle between the primary beam and detector directions: the object itself screens some emitted electrons from the detector

    Xresolution down to -2nm possible with ultrasmall spots and thin samples (to minimise size of scattering volume)

    XSE imaging used widely in electronics industry for routine imaging of devices

<*Backscattered electron (BS) image* also shows specimen surface topography and, in addition, carries information about sample *atomic number* and crystal structure

    Xas the elemental atomic no (Z) increases, so does the efficiency of electron backscattering

        Bthe intensity of the BS image increases with specimen atomic no

        Blocal areas of different elements, in principal, can be distinguished (so-called *Z-contrast*) and elemental maps can be produced

    Xfor a crystalline specimen, so-called channelling or Coates patterns useful for assessing crystallinity of sample can be produced

ii) Charge Collection Mode

<The basic current supplied by the beam, passing through the sample, can also be used for imaging

    Xgives a so-called *absorbed current* image complementary to SE and BS images (these signals are removed from the measured current)

<If an electrical barrier, such as a p-n junction, a Schottky barrier (contact) or a heterojunction, is present in the specimen, a current is produced in an external circuit when the beam scans the barrier

    X*electron beam-induced conductivity* (EBIC) signal produced as beam-induced carriers (electrons and holes) are swept apart by the internal field

        Bvariations in barrier (junction) properties are revealed as contrast changes: important for *device inspection*

        Belectrically-active defects in the junction region lower carrier lifetime and, hence, reduced EBIC signal

            defects give EBIC contrast in scanned image and can be detected and studied

iii) Voltage Contrast

<SE detector is modified in order to allow selection of electrons of different energies

    Xpossible to observe or measure small differences of electrostatic potential over probed surface

        B*voltage contrast* is obtained due to change in escape probabilities for secondary electrons across their energy range

        B*quantitative* variations in contrast allow measurement of voltages at specific points in operating ICs: *e-beam testing*

    Xwhen IC voltage is static, only a static measurement is needed

Xwhen IC voltage varies, observation/measurement must be electrically gated in-phase with the IC signal

B*stroboscopic voltage contrast*

iv) Cathodoluminescence Mode

<Optical photons (*cathodoluminescence*) emitted by irradiated specimen collected and analysed

Xeg, a parabolic mirror over the specimen collects the light and directs it either into a PMT, or, into a spectrometer/detector system

Bsystem must have high efficiency since signals are often low

Xallows formation of 'total light' images or emission spectra and wavelength-selected images

Bprovide detailed, spatially-localised assessment of semiconductor *electronic and optical properties*

Xexample of assessment of quantum wires formed by growth in V-grooves

v) X-Ray Microanalysis

<X-rays emitted by irradiated specimen collected and analysed

XX-ray detector gives *spectrum* of photon intensity vs photon energy

B*energy-dispersive detector* (in common use) gives parallel collection but with relatively poor energy resolution and peak/background ratios

cooled Li-drifted Si p-i-n diode

B*wavelength-dispersive detector* gives only serial collection but with much higher spectral resolution and excellent peak/background ratios

crystal-diffraction spectrometer with proportional counter

Xpresence of *characteristic X-ray spectral peaks* is used to detect presence of specific elements: peak amplitudes give quantitation

B*spatial resolution* -0.1-$1\mu m$ for bulk specimens

B*sensitivity* -0.1-1% for energy-dispersive detector

7(a) Secondary Ion Mass Spectrometry

<Used to study the *internal/near surface* composition of materials

Xrequires only bulk specimens

! Principle of Technique

<0.5-30kV *primary ion beam* is formed in high vacuum and either

Xfocused to a small spot of -1-$20\mu m$ in diameter and scanned, or

Xmaintained as large flood beam

<Beam impinges on sample to be analysed and, due to near-surface scattering, ejects *secondary ions*

Xsecondary ions are mass-analysed using a spectrometer to give sample *composition analysis*

Xerosion of sample by primary ion beam allows composition *depth profile* to be obtained   (Figure useful)

! **Instrumentation**

<Two types of instrumentation (Figures required)

X the ***direct imaging ion microscope***

B spatial distribution of the extracted secondary ions is retained as they pass through the mass spectrometer

B mass-resolved ions imaged by a micro-channel plate or counted by a multiplier

B lateral resolution $-1\mu m$

X the ***raster scanning ion microprobe***

B uses digital scanning of finely focused ion beam to obtain lateral and depth information from the sample

B lateral resolution $-1\mu m$ or less

<Selection of ***primary ions***

X electronegative primary ion species (typically oxygen, O^- or O_2^+) enhances positive secondary ion yield

X electropositive primary ion species (typically cesium, Cs^+) enhances negative secondary ion yield

B primary ion selected according to electropositive or electronegative character of sample elements, for ***optimum sensitivity***

<***depth resolution*** as high as $-2nm$

X determined by secondary ion escape depths and ion mixing in sample surface layers
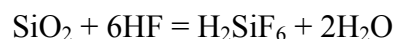
X degraded if nonplanar surface topography develops

7(b) **Etching of Insulating Films**

<Etching is used typically to pattern oxide or nitride layers

X Wet and dry etching techniques are employed

<***Wet chemical etching***

X SiO_2 layers are readily etched in hydrofluoric acid

$$SiO_2 + 6HF = H_2SiF_6 + 2H_2O$$

B such etching is typically carried out either directly with HF solution (***low pH***) or using HF solution with added NH_4F as a buffering agent (***high pH***)

X Si_3N_4 layers can also be etched with HF and buffered HF solutions

B selective Si_3N_4 etching in the presence of oxide can be achieved using ***phosphoric acid***

<***Dry etching***

X Ions atoms and radicals are formed in a plasma by ionisation and fragmentation

B etching is produced by ***physical sputtering*** and/or catalysed ***chemical reactions***

Breactive ion beam etching (RIBE) relies on chemical reactions to produce volatile compounds

Btypical dissociative reaction in a CF_4 plasma:

$$CF_4 + e^- = CF_3^+ + F^- + e^-$$

XGas composition determines etching rate and selectivity

B*halogen*-containing gases are used to etch Si, SiO_2, Si_3N_4 and Al

B*oxygen*-containing gases are used to etch photoresist and organic layers

<Etch characteristics

X*Dry etching* characterised by high selectivity and pronounced directional etching ability

Bfavoured for ULSI technology due to etch *dimensional accuracy*

XComparison of wet and dry etching (Figure useful)

BSiO_2 on Si is covered with resist, which is then photographically exposed and   patterned

B*wet chemical etch* dissolves the exposed oxide in an *isotropic* manner and progressively undercuts the resist

B*RIBE is highly anisotropic* and produces parallel-walled etched regions with dimensions closely similar to those of the original resist pattern

ideal for the very small structures characteristic of ULSI circuits