2006 MET2 Paper 1 – Crib

Question 1

(a) The terms all refer to specific sub-processes of the overall IC manufacturing process:

(i) Epitaxy is the growth of an ultra-pure layer of crystalline silicon onto the base silicon wafer. It is approximately 3% of the thickness of the original wafer and has to be contaminant-free for the subsequent construction of transistors.

(ii) Photolithography is the process of forming the pattern of the integrated circuit on the surface of the wafer. This is done by coating the surface with a photoresist material, and then exposing the wafer to an image of a layer of the circuit, by means of a lens and light source. The image is contained in a mask (or reticle) through which the light shines onto one or more die. The wafer is then stepped over to the next die(s) until the whole wafer is completely exposed.

(iii) Diffusion and implant are the two ways of inserting dopant materials into the pure silicon layer in order to create different semi-conducting properties. Diffusion involves deposition of the dopant chemicals onto the surface and then their diffusion into the silicon. Implantation involves the bombardment of the silicon surface by an ion implant beam. The regions of differing semi-conduction properties become the source and the drain of the CMOS transistor.

(b) The yield values relate to the main physical stages of the IC manufacturing process at which yield can be measured and the process controlled to improve yield (see points identified on the chip making process diagram):

(i) Wafer processing yield measures the useful physical area of wafer produced by the end of the wafer manufacturing process and before testing of individual circuits on the wafer. This is affected by the crystal growing, grinding to size, sawing and handling processes, and is related primarily to the physical robustness of the wafer.

(ii) Wafer probe yield is a measure of the number of good quality circuits produced on the wafer as a percentage of the total number possible on the wafer. This is affected primarily by the fineness (pitch) of the circuit and the cleanliness of the process. Contaminants and lack of precision in process equipment will result in faulty circuits.

(iii) Assembly yield measures the accuracy of circuit connection to the chip. Gold wires are attached to the edge of the IC to make these connections. The yield is affected by the stability and control of the edge-connecting machine.

(iv) The final test measures the performance of the complete encapsulated (in plastic) IC. The main sources of yield loss at this stage are mechanical damage during the encapsulation process.

The overall yield for the manufacturing process is given by the multiplication together of the yields at each stage. In this case:

0.94 x 0.50 x 0.96 x 0.90 = 0.41, or 41%

(c) Integrated circuits are manufactured for a variety of purposes, the main ones being microprocessors, DRAM (dynamic random access memory) and ASICs (application specific ICs). Yield tends to decrease as the complexity of the chip increases, and the main source of variation is detected at the wafer probe stage. A simple logic chip might achieve a yield of over 90% at this stage, whereas a complex microprocessor or RAM chip might be as low as 5%. The complexity is related to the number of transistors in the circuit, and the line width of the circuitry. Reducing line width means that the actual die size can be reduced, thus placing more dies on the wafer and increasing yield for a given clean room condition. The economic incentive to increase yield results in the drive for a cleaner manufacturing environment (less contamination and unwanted particles), and also a larger wafer diameter in order to harvest more of the physical area of the wafer – and hence more dies.

Examiner's report

This question was answered well by most candidates. As parts (a) and (b) of the question were structured into a number of sub-sections requiring definitions and applications, it was very clear which candidates really understood the material and those which attempted to waffle. Part (c) gave more scope for candidates to demonstrate understanding of the manufacturing of different types of integrated circuits, and showed a range of marks between those that structured their answers well and linked it back to themes raised in (a) and (b), and those that attempted to write around the subject in general terms.

Question 2

(a)

(i) Stereolithography: bath of liquid monomer resin, laser beam focused beneath the surface causes local polymerisation (photolytic cross-linking and thus hardening) of the polymer. The beam is scanned through the bath in a raster mode, in slices upwards, building up a 3-D shape of solid polymer under software control. Part removed from bath and remaining liquid monomer drained/washed away. Process limited to photopolymerisable thermoset materials (expensive), and applications of this material restricted to prototyping applications – exploration of shape, aesthetics, fit into assemblies etc. Can also be used as mould/pattern for other manufacturing processes. Maximum resolution ca. 25 μm.

(ii) Selective laser sintering: shape built up by scanning laser beam across top of bed of powder (thermoplastic or metal). Laser beam causes local fusion/bonding/sintering of particles. Layer of fresh powder then applied to top of bed, which moves downwards one step, and process repeated. 3-D shape built up by progressive raster scanning of slices. Finished part removed from bed and unbonded powder removed. Process restricted to thermoplastics and metallic powders – metal parts can be further sintered in oven to reduce porosity and increase strength. Polymer/metal blends and polymer/ceramic blends also possible – then sintered (cf metal injection moulding). Parts can have much higher strength than stereolithography and the process can be used for production (short runs) as well as prototyping. Also useful as process for making tooling (eg dies for short-run plastics injection moulding). Maximum resolution ca. 50 μm.

SLS and some other additive manufacturing processes (e.g. fuse deposition modelling) can be used for manufacturing – advantages over conventional processes: cost per part same whether batch size of one or 1000; bespoke designs, changes to geometry etc easy to incorporate via CAD file; minimal set-up time; no tooling/die costs; shapes can be produced which are uneconomical or impossible to produce by other methods. Disadvantages – significant production time per part so much slower for larger production runs; limitations in materials available; materials may be expensive; post-processing (eg sintering) may be needed for some materials/applications.

(b)

(i) anodizing – process used to increase the thickness of the oxide layer on the surface of metals. Restricted to certain metals – major ones being aluminium, magnesium, titanium. Object to be anodized is placed in a bath of acid (usually sulphuric acid) and made the anode (positive electrode) in an electrolytic cell. Current passed and oxide grows. Typical oxide thickness 20 – 50 μm. Aluminium oxide much stronger/harder than aluminium – provides protection against corrosion, mechanical damage. Anodized layer can be dyed, and can also incorporate lubricant materials (eg PTFE particles)

(ii) HVOF spraying used to produce thick (10 – 10 μm) layers of almost any material which can be melted. Powder of coating material is injected into flame emitted from combustion gun fed with fuel gas (eg hydrogen or propane) and oxygen. Rapid expansion of combustion products gives high temperature and high velocity (to 550 m/s) of molten coating droplets, which then strike surface to be coated and fuse together to give high density, strongly adherent coating. Can be used for metals, ceramics and polymers, on any substrate (although it must withstand some heating)

(iii) PVD (physical vapour deposition) coating involves transport of coating material to surface to be coated by physical (rather than chemical means). Three basic groups of processes, all carried out in low pressure gas. Evaporation involves heating molten coating material (eg aluminium) and allowing material to evaporate (boil off) and condense to form coating – used for example to coat polymer sheet for packaging. Adhesion is poor as energy of coating atoms striking the surface is low. Energy can be increased in sputtering where a solid target of coating material is used, and is struck by gas ions (eg argon) which then eject (sputter) uncharged atoms of coating material out to strike the object to be coated. Adhesion is better. In ion plating, a gas discharge in low pressure argon generates ions which then collide with atoms of coating material which are evaporated from a molten source, causing them to ionize. The coating ions are then attracted to the (charged) object to be coated. All these processes can be combined with chemical reaction at the surface (eg Ti ion plating in presence of N gas gives TiN coating by reactive ion plating). Typical coating thickness 2-5 μm. PVD processes are usually used for coatings of metals or metallic compounds such as nitrides or carbides.

(c) Garden spade is stainless steel and anodizing is <u>not</u> suitable for this material. In principle HVOF or PVD processes would be possible – but we need to establish what the coating material should be, and how thick it needs to be (noting that PVD coatings are much thinner). For this application we need to reduce the friction and also reduce the wear, so that we need to consider the wear rate of the coating material and the design life of the spade. The application is innovative and tests would be needed to decide on the best coating – datasheet information would not be enough. A development project should address at least the following technical and business requirements:

- identify possible coating materials – these might include some polymers (low friction), ceramics (very hard) – possible some metals if hard enough (eg electroplated chromium)
- identify appropriate coating methods for these materials in collaboration with potential suppliers
- obtain samples of coatings with suitable geometry for testing
- design and carry out some small-scale (lab-scale) tests to evaluate wear rates and friction against soil for coating samples
- business plan for producing spades with the best-performing subset of these coatings (coating applied in-house or subcontract, market prediction etc.)
- identify best candidate coatings from performance and business information
- make up prototype spades with these coatings and perform consumer trials
- use all information from above steps to decide optimum coating

Examiner's report

Overall this question was answered fairly well. Good answers to part (a) were those which not only described the processes but also showed understanding of restrictions on materials which can be used. Many of the poorer answers missed out this second part. Many students gave examples of commercial processes without going into much detail on the opportunities these presented, other than in very general terms. Part (b) was answered satisfactorily by most candidates, but few were able to describe the limitations of each process. Part (c) gave an opportunity to apply this knowledge to a real world problem – most candidates were able to work out which process would not be suitable (anodizing) and could illustrate strengths and weaknesses of remaining two. Some chose not to discuss the processes from part (b) at all. Few were able to describe a detailed development plan that merged technical and commercial issues.

Question 3

(a) Sustainable manufacturing focuses on reducing the environmental impact of production. Lean manufacturing involves minimizing stock levels, resource usage, waste generally within the context of a factory or industry sector. Sustainable takes this as a starting point, but also looks at wider influences: for example, looking at the environmental impact of materials production or disposal. It may also, depending on how tightly the definition is drawn, take on sociological issues.
Five approaches which can be sued to achieve a more sustainable manufacturing process are:

- use less material and energy
- substitute input materials: non-toxic for toxic; renewable for non-renewable.
- reduce unwanted outputs; cleaner production, industrial symbiosis
- convert outputs to inputs; recycling and all its variants
- changed structures of ownership and production; product service systems, supply chain structure

(b) Impacts can be on one or more phases of vehicle lifecycle: manufacture, use, end of life.

Manufacture: numerous examples of ways in which manufacturers are currently improving operations. Reduction in toxic by-products. Common platforms can reduce stock levels. Good design can reduce waste (e.g. press small parts from offcuts from larger sheet pressings). For the future, localised production: reduction in transport.

Use: over-riding consideration is design for fuel efficiency. Alternative energy sources becoming more important as well.

End of life: design for disassembly, recyclability. Current legislation requires significant recycling, but in some cases this many simply mean diverting from landfill rather than allowing the material to be reused in high quality applications.

Changes in ownership: manufacturers retaining ownership of vehicles means they will pay more attention to end of life issues. Cost-cutting at the manufacturing stage may be less important if it impacts on the whole life-cycle. There could be significant eco-savings from manufacturers retaining ownership. A lower type of ownership change which some may think of is car-pooling, which may reduce the number pf vehicles slightly and increase usage of individual vehicles, but the overall impact will be slight.

(c) CFRP production involves separate production of carbon fibre (from drawn polymer precursor filament - polyacrylonitrile PAN – which is carbonized by heating and drawing in a controlled atmosphere) and unpolymerized resin sheet. Fibre and resin sheet then combined in rolling process to form prepreg sheet which is laid up by hand or automatically (tape layer) on to moulds of correct shape. Uncured composite is then vacuum-bagged and autoclaved (heated under gas pressure) to cure to final shape/properties. Sources of waste at all stages. During prepreg manufacture in solvent evaporation, in cutting/forming of prepreg in offcuts etc., in backing sheets, shipping/handling aids, in scrap parts. Waste reduced by use of solventless formulations, better design of shapes/cutting program to use more of sheet, automated tape/fibre layup, better quality control at all stages to reduce scrap.

CFRP used for high-performance, high-cost specialised applications (eg racing cars, aerospace). So waste material at end of use will be concentrated in small number of relatively sophisticated customers (eg government agencies, airlines, racing teams) and therefore in principle access for recycling is easy (no problems in collection, sorting etc). However, the nature of the high strength thermoset resins and the carbon fibres themselves means that recycling as high-performance composites is not possible. Furthermore, current volumes are not large so driver to recycle is not great.

Polymers used for domestic packaging in contrast are predominantly thermoplastics, in very large volumes, and at end of use are widely dispersed, mixed and contaminated. Although individual thermoplastics are in principle recyclable, there are major challenges in collection, sorting and cleaning of these materials before recycling (other than by burning) is possible.

Examiner's report
Most students were able to present approaches to sustainable manufacturing very well and this led to overall high marks for part (a). Part (b) led to some more rambling answers, but strong attempts were those that gave structure to their discussion (considering issues relating to manufacture, use, and end of life). The first section of Part (c) was answered pretty well, with candidates able to describe the basic process, but not many able to really focus in on sources of waste. The second section of (c) was not particularly well answered as many candidates did not seem to have much knowledge of polymer and CFRP recycling.

Question 4

(a) Process Intensification (PI) is a term used to describe the strategy of making dramatic reductions in the size of a chemical plant in order to reach a given production objective. The concept was pioneered in ICI during the late 1970s, when the primary goal was to reduce the capital cost of a production system. The virtue of the PI approach can be realised when the main plant items involved in the process (i.e. reactors, heat exchangers, separators etc.) only contribute around 20% of the cost of a given plant. The balance is incurred by installation costs which involve pipework, structural support, civil engineering and so on. A major reduction of equipment size, coupled preferably with a degree of "telescoping" of equipment function - for example reactor/heat exchangers or combined condenser/distillation/re-boilers - could generate very significant cost savings by eliminating support structure, expensive column foundations and long pipe runs.

In addition to the installation costs, current process plant is large and the use of high volume chemistry leads to physical limits, i.e. limited rates of mixing, diffusion, reactions and heat flow. Hence large scale infrastructure is required to deliver the required production volumes. (PI) is a highly innovative concept in the design of process plant. The aim of intensification is to optimise capital, energy, environmental and safety benefits. Process intensification can be an important means in reducing the costs of process integration, and process performance.

(b) (i)

<u>The benefits of may be summarised as:-</u>

Intrinsic safety: If equipment volumes are reduced by a factor 0f 100-1000, then flammable/toxic inventories will present much less of a threat to the environment/population. For example a large distillation column, with reboiler and condenser may contain 100 tonnes of hot, high pressure hydrocarbon. An intensified plant would probably have prevented disasters like Flixborough and Bhopal.

Environmental impact: Conventional process plant is dominated by pipework, tall columns and cooling towers which spoil landscapes and affect the quality of life of local communities. Intensified plant can be hidden by trees at the boundary fence so plant can be harmonised better with its surroundings. There is also the opportunity for Lower waste levels reduce downstream purification costs and are conducive to "Green" manufacture economic distributed.

Energy efficiency: The improved heat and mass transfer coefficients which may be achieved in intensified equipment may reduce the system irreversibilities represented by:

- Temperature
- Concentration differences

This can improve the thermodynamic efficiency of

- Reactors

- Separators
- Energy transformers

Better product quality: More efficient controls over reaction rates and operating conditions lead to improved product quality.

Just-in-time manufacture becomes feasible with ultra-short residence times.

Distributed (rather than centralised) manufacture may become economic allowing point-of-use or point-of-sale process technologies. There is also the opportunity for cost savings by avoiding transport of hazardous material.

PI can help companies and others meet all of these demands, in the process industries and in other sectors

(b) (ii)

<u>The problems of exploitation of may be summarised as:-</u>

Step changes in equipment design/operation are involved. This creates problems when there is already an established process investment costing hundreds of millions of pounds, as it will be exceedingly difficult to justify a “scrap and start again” policy.

For PI to be fully effective, a very wide range of technology must be developed covering all of the main unit operations.

Most plant managers “rush to be second” and require full scale evidence of successful operation before they are prepared to take a any risk.

Design codes are needed for new equipment, these are not fully developed as the science and engineering of micro-flows is still in its infancy.

There is a need to distinguish between slow (>5s) and fast (<5s) reactions. Different PI technology will be needed for each regime.

The culture shock in batch dominated industries will be difficult to overcome.

Microfluidic systems are particularly prone to fouling, this is especially important for multiphase and particulate flows, such as those found in pharmaceutical and food industries.

c) Because the efficiency of a chemical reaction is determined by the ability to transfer reagents and energy in and reactants out of a reaction zone, plant designs using small length scales can significantly affect reaction and heat transfer rates. As can be seen from the equation for heat transfer, the rate of heat flow is directly proportional to the concentration gradient. PI allows the thermal gradients to be increased enormously through the use of very narrow channels (100’s of microns wide) into which reagents are delivered. The increased heat flow rates lead to fast reaction rates and greater yields. In order to make the PI principle cost effective, large bore delivery pipes are replaced by a collection of micro channels in sufficient volume to deliver the necessary production volumes equivalent to those of large bore pipes. PI based boilers, condensers, gas/liquid reactors, and heat exchangers all benefit from the ability to increase heat transfer rates.

Examiner's report

Part of the reason for the low average mark for this popular question was a failure of most students to answer part (a) in sufficient detail. Of the available 20% for describing PI, most candidates were marked at under 10 % for their attempts.

Part (b) gave the candidates the opportunity to bring in practical commercial examples, with strong answers to this part being those that structured the issues and examples around clear themes.

Most candidates could address the main issues of part (c) but to widely differing degrees of detail.

Question 5

(a)

(i) Customer Service
<u>On time in full delivery</u> – the percentage of customer orders delivered at the agreed time and place and complete in all respects including supporting paperwork.
<u>Customer complaints</u> – the percentage of customer orders giving rise to a complaint

(ii) Internal Efficiency
<u>Added value per employee</u> – Sales turnover less costs (fixed + variable + overhead) divided by total production staff
<u>Overall Equipment Effectiveness</u> – Product Rate Efficiency x Quality Rate Efficiency x Availability (or one of several other definitions all of which amount to [Actual output/Theoretical maximum output] while differentiating between rate losses, quality losses and availability losses.

(iii) System Performance
<u>Schedule Adherence</u> – Percentage of shop orders completed to schedule (measure of planning and scheduling processes)
<u>Changeover times</u> – Time taken to change from one batch to another (measure of flexibility)
<u>Inventory Record Accuracy</u> – proportion of sku's or stock locations where actual quantity counted equals the quantity recorded on the inventory system.

Note: Other measures, properly identified and defined will be acceptable.

How might you use benchmarking in this assessment and what plants would you use for comparison?

Monitor key parameters across comparable lines in the group and with other baking firms where consistent data can be obtained. Also see best achieved data from similar process and plant from different businesses (e.g. Food industry lines with continuous or semi-continuous front end stages feeding higher variety packing lines).
Obtain relevant World Class figures for headline measures such as OEE, OTIF.

(b) (i)

Product Rate efficiency — *Product rate efficiency = 97% (given)*

Quality Rate efficiency — *Waste product = 1% + 2% + 1.5% = 4.5% Packing waste on the bread line is a bit lower, but value low. Take Quality rate efficiency as (100 – 4.5)% = 95.5%*

is also

Availability *There are 13 x 12 hour shifts per week (12 production and 1 maintenance) = 156 hours.*
Scheduled outage is 12 hours + 12x(40+20)/60 = 12+12 = 24 hours or 24/156 = 15.4%
Unscheduled outage is 12x30/60 = 6 hours or 6/156 = 3.8%.
Total outage = (15.4+3.8)% = 19.2%
Availability = (100-19.2) = 80.8, say 81%

(b) (ii)

Hence the Overall Equipment Effectiveness (OEE).

OEE = (0.97x0.955x0.81) = 75%

What value of OEE would you set as an improvement target for the bread line and why?

World Class OEE for batch plant is 85% and for continuous plant is 95%.
Bread line should initially target 85% with perhaps 90% later. (Answer is acceptable in the range 85% to 95%).

What % increase in weekly throughput on the bread line could be achieved if this target were met?

85/75% = 13% increase and pro rata up to OEE of 95% (20% at 90% OEE, 27% at 95% OEE)

(c)

(i) Communicate need and outline proposed programme – "work smarter not harder" message.
Conduct initial training for worker involvement (e.g. TPM 5S)
Collect data systematically with worker participation
Introduce 5S (or equivalent) to <u>maintenance workshop</u> operation

(ii) *Measure and understand losses*
Clean, tidy, organise, standardise, sustain. (The 5S approach and mindset)
Kaizen – continuous improvement
Employee involvement
Root cause analysis – 5 why's
Elimination of waste
Visible processes, charts

Examiner's report

This question combined quantitative and qualitative aspects and produced some excellent answers. The question required the candidates to draw key points from a relatively large amount of information. Most were able to do this well, as is reflected in the relatively high average mark. The quantitative aspects of the question were generally handled well with the best answers illustrating a clear understanding of the underlying principles. Many of the qualitative, discussion sections were insufficiently focused around actually answering the question and just drew in selected issues rather than showing evidence of structured analysis.

Question 6

a) The advances in machine tool technology have been aimed at building machines, which can manufacture a component from raw material to finish machined in one set up. This vastly reduces throughput times by reducing all the queueing, and transport associated with multi machine, multi set-up manufacture. With CNC control labour input is also significantly reduced.

In order to achieve this the number of controlled axes has increased dramatically. It is now difficult to classify machine tools as machining centres, or CNC lathes as these two main types are becoming merged. Candidate should discuss in detail the state of the art characteristics of each.

CNC lathe. – will now typically have two driven spindles (C axis) to allow for both ends of a component to be machined. Each spindle will be under full CNC control allowing indexing to typically 0.0001 degree. Typical spindle speed of 5000 rpm allows high speed machining.

The x axis will typically carry a turret carrying 8-10 tools. There may even be a secondary turret which may have driven tooling.

There will be a milling spindle (B axis) capable of say 12,000 rpm . This will be supplied with an automatic tool changer.(20-40 or 80 tools are typical options) The B axis will be capable of rotating through a wide angle (again under full CNC control) This will enable face machining, milling drilling etc. It will likely be equipped with through spindle coolant to allow deep hole drilling. The high speed of the spindle allows the inclusion of grinding operations, and machines can have an optional wheel dressing facility built in.

Real advantage coming from the simultaneous, synchronised driving of multiple axes, this allows operations such as gear hobbing, cam milling etc which, in the past, would have been carried out on dedicated machines.

Advances to chuck design, using hydraulically driven pins to grip, enable almost all shapes to be held without custom designed tooling.

Advances in CNC programming using computer assistance allow for the rapid production of programs. Conversational programming for simpler jobs.

Automatic tool inspection, measuring and compensation on the machine to speed set up; sister tooling to cope with wear, breakage.

CNC Machining centre

Very similar approaches. The main table will likely be provided with a tilting and rotating precision table, providing A and C axis. Full CNC of X,Y,Z,A,C axes. High speed spindles, large tool changers, 80 ,120 typical. Pallet changers to allow extended periods of unmanned operation.

(b)

Problem	Potential Solution
Work Holding: Integration of grippers, requirement for handling both raw material and finished product	Software handshaking, use of 'soft –float' function on robot, flexible grippers or reversible (multi) end effectors.
Robot dexterity and payload capability at extended positions	Correct choice of robot, ensuring sufficient axes and taking account of loads
Access to Machine	Motorised guards, sensing and interlocking required
Swarf clearance	High pressure air jet; coolant swarf separation, swarf conveyors
Control integration	If robot serves only one m/c tool, can be done through machine tool controller interfacing directly with robot controller. If multiple machines – plc control required.
Ancilliary operation (such as deburring) will probably require some form of sensing	Soft float
Transport to and from cell	Although not explicitly addressed in the question, the means of getting material and parts to and from the cells requires thinking about. In a fully automated system, a conveyor system or AGV will need integrating and this raises the level of complexity.
Errors	A major activity in integrating is to try to anticipate all the potential things that might go wrong, to put sensors in place to detect errors and to provide error handling routines. These may be automatic correction routines or may involve stopping the cell and requiring operator intervention

Examiner's report

Most of the small number of candidates who attempted to answer this question misunderstood what was being asked of them and attempted to present material that was entirely inappropriate. In part (a), rather than discussing machine tool technology, they described instead rapid manufacturing (additive) technologies such as SLS. Part (b) was handled slightly better, but marks for this for some of the candidates were also very low as they did not answer the question in sufficient depth.