Jason Taylor

Transistors and Global Culture. Contributions of Chemical Engineering

Around the globe, daily life has been significantly affected by the semiconductor industry, for example, by transistor technology. Process improvements have enabled mass production of transistors, lowering costs sufficiently to make numerous electronic products widely available. Digital camcorders and cameras, cell phones, global positioning systems (GPS), personal computers and laptops are now affordable for millions of people around the world. Although electronic products have been developed primarily by physicists and electrical engineers, chemical engineers have also contributed to transistor fabrication through the creation of pure bulk silicon crystals, epitaxial growth of thin films, and diffusion of dopants into the metal oxide layer. Cultural changes have resulted from lowered costs of transistors; chemical engineers have helped to produce the transistors required for modern electronic devices.

Cultural Impacts of Transistor Technology

Over the last 20 years, improvements in semiconductor processing have lowered costs of personal computers, triggering the development the world wide web (a.k.a. the internet). Since 1990, the internet has changed life significantly. Bill paying and bank account management are predominantly handled online due to ease and convenience of making payments and monitoring account activity. Retail sales of manufactured and second hand goods are conducted over the internet, increasing sales figures through greater exposure of advertising. As conducting business online increases, personal interaction and security decrease, especially when customer support is needed; for example, calling customer service often consists of listening to an automated computer system that directs the customer to a prerecorded solution. Additionally, live customer support is outsourced to foreign countries and offered via telephone, making communication difficult. Electronically transmitted information can be intercepted by malicious users leading to identity theft and credit fraud. These issues can often be resolved but require much time and effort with no guarantee of success.

Job recruitment and application begins online for positions ranging from customer service to chief executive officer, offering employers a large pool of candidates and workers a vast array of employment opportunities. Little connection is made between employer and employee until interviewing has begun. This raises the question of whether the most qualified or the best “personal marketers” are recruited. Many qualified applicants miss out on job opportunities due to the impersonal nature of modern day recruitment.

Information such as news on current events, personal health and fitness practices, and medical advice is available online. Many periodicals, encyclopedias, books, magazines, and other literature have been electronically stored, often in lieu of keeping hardcopies. Information at the fingertips of the user promotes faster learning, but not all of the information online is reliable. Unless the source is credible (for example, an online encyclopedia or scientific journal), it is difficult to discern the validity of the information. Unreliable information is misleading, and causes confusion. Even when information comes from a credible source, it is often better to use hard copies because it is difficult to refer to several online resources simultaneously.

Some colleges offer education online, providing students with the convenience to watch lectures or work on assignments at leisure. This is convenient for those who have jobs and need their school schedule to cater to their availability, but there are significant drawbacks. Students watching a prerecorded lecture must submit questions via email, and the quality, promptness – even the probability - of a response depends on a distant, probably overworked professor. Additional help is more difficult to obtain when online resources are insufficient. Again, there is a lack of social interaction, an emerging theme as society strives for more and more convenience. Because many online colleges lack the academic credentials of well established universities the quality of education obtained from these institutions is doubtful.

Social interaction is now conducted via email and online networking, on sites like www.myspace.com and www.facebook.com. Networking with hundreds of correspondents across the globe is now convenient, making it easier to meet and talk with new people. Dating websites promise to find your perfect match, taking away all the discomfort and nervousness of approaching an attractive stranger. But electronic relationships without face-to-face interaction are often shallow. Deceit is common and often the impression of someone met online varies dramatically from reality. Bypassing traditional dating, handicaps people emotionally because they cannot easily portray themselves honestly to others.

Digital graphics and computer gaming have seen tremendous improvements. Hollywood now spends more resources creating special effects via computer than on encouraging talented acting. Filled with amazing visual images, modern movies often have a weak plot and subpar acting. Similar to the movie industry, gaming has also focused heavily on graphics in lieu of plot development. In addition, online gaming serves as another form of social networking. Millions of people become enraptured by a fantasy world, exploring an electronic frontier, making friends and enemies with other gamers around the world. Although this activity can provide a release from everyday worries, the feeling of conquest is addictive and many gamers trade their real life for a fictitious one. Hours are spent daily seeking power and riches in an electronic fantasy land.

The music industry has also been heavily impacted as most music is available online, lowering the incentive for consumers to purchase CDs. Despite a decline in CD sales, the number of new artists emerging is increasing but their careers are short lived, often lasting fewer than 5 years, unlike the musical icons of yesteryear, such as Elvis Presley and the Beetles, who remain popular to this day. Websites such as www.youtube.com allow users to upload videos for others to view at leisure. People post videos of themselves entertaining in various ways, like singing or dancing, leading to possible recruitment by talent scouts. One example is

Arnel Pineda, the current lead singer of the rock band Journey. Arnel Pineda played in a rock cover band in the Philippines, and was scouted by band members of Journey on youtube.

Aside from influencing the internet, transistors have bolstered pure and applied research in a numerous fields. Transistor improvements have increased information storage capacity, processing speed, and the ability to run multiple processes simultaneously. Advances in biology, medical devices, pharmaceuticals, and photo voltaic cells, to name a few, can be attributed to the capability of modern day computers that rely heavily on new transistor technology. Additionally, electronic devices are becoming smaller and their capabilities are increasing. Modern cell phones can play music or movies, take photographs, record videos and surf the internet. All of these developments have transformed daily life, especially for young people, since about the year 2000.

Contributions of Chemical Engineers towards Transistor Fabrication

Methods for making transistors result from the engineering efforts of many disciplines, including electrical, chemical and material science engineers and physicists. Towards the fabrication of transistors, three essential contributions of chemical engineers include the creation of pure bulk silicon crystals, epitaxial growth of thin films, and diffusion of dopants into the metal oxide layer. These three fabrication techniques use fundamental concepts of chemical engineering science, including chemical reaction, heating and cooling, boundary layer theory, and diffusion.

Bulk Silicon Crystal Growth

Creation of pure bulk silicon crystals begins with preparing starting materials from quartzite, a relatively pure form of silicon dioxide (essentially sand). Silicon dioxide is reduced in a submerged arc furnace at 2000^{o}C by reacting with carbon according to;

$$SiO_{2(s)}+2C_{(s)} \rightarrow Si_{(l)}+2CO_{(g)}$$

A submerged arc furnace is an electric arc furnace that heats the slag (silicon dioxide in this case) with via arcing between electrodes embedded within the slag. The resulting molten silicon is 98% pure and referred to as metallurgical grade silicon (MGS). Powdered MGS is then converted to trichlorosilane in a fluidized bed reactor at 300^{o}C according to;

$$Si_{(s)}+3HCl_{(aq)} \rightarrow SiHCl_{3(aq)}+H_{2(g)}$$

Contaminants present in the 98% pure MGS and their respective products reside in the aqueous trichlorosilane. The main contaminants are the halides of iron, aluminum and boron; all possessing boiling points greater than that of trichlorosilane, which boils at 31.8 ^{o}C. Purification is achieved through fractional distillation. The trichlorosilane is then converted into electronic grade silicon (EGS) by the following reaction, and chemical vapor deposition is used to deposit the EGS onto a thin high purity silicon rod;

$SiHCl_{3(g)}+H_{2(g)} \rightarrow Si_{(s)}+3HCl_{(g)}$

Crystal growth can now begin. The Czorchralski process, one of many crystal-growth processes, starts by melting EGS into a crucible and bubbling in an inert gas to prevent oxidation to silicon dioxide. A silicon seed crystal is then lowered into the molten EGS and allowed to melt partially before it is withdrawn at a controlled rate, rotating in the direction opposite to the rotating crucible. The seed acts as a template for the atomic arrangement of the molten EGS as it solidifies. The maximum pull rate is expressed as;

$$v_{max}=K_{Si}(dT/dx)/(L\rho) \qquad (1)$$

where K_{Si} is the thermal conductivity of silicon, dT/dx is the axial temperature gradient, L is the length of the ingot (a material that has been cast into a specific geometric shape for further processing), and ρ is the density of solid silicon. The resulting ingot is then sliced and used for transistor fabrication.

Epitaxial Growth of Thin Films

Epitaxy is the only affordable method of depositing a monocrystaline film on top of a monocrystaline substrate, where the substrate acts as the template for a particular desired atomic arrangement. Liquid phase epitaxy, one of many epitaxial techniques, is common in industry because it is inexpensive, simple to apply and capable of producing complex layered structures. A solid substrate of AB, where AB may be Ga-As for example, is brought into contact with a melt that contains both A and B. To grow a layer of AB on the substrate, B atoms must diffuse through the boundary layer to the solid surface as shown in figure 1.

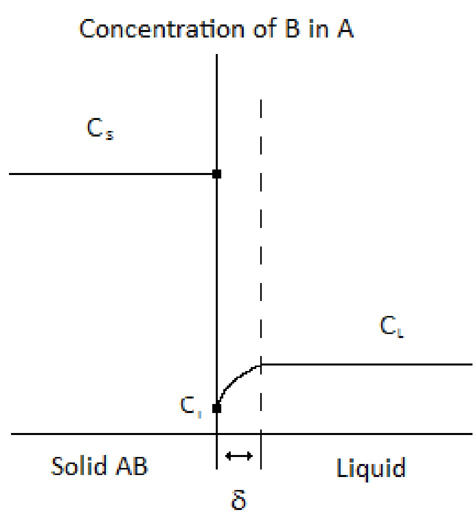

Figure 1: Substrate-melt interface during liquid phase epitaxy.[1]

The flux of B atoms to the surface (J) and the growth rate of the epitaxial layer (R) can be calculated by

$$J=D(C_L-C_l)/\delta \qquad (2)$$

$$R=D(C_L-C_l)/\rho\delta \qquad (3)$$

where D is the diffusivity of B in A, C_L and C_l are the concentrations of B in A in the bulk liquid and at the interface, respectively, δ is the boundary layer thickness, and ρ is the density of solid silicon. Layer thickness depends on how the liquid phase epitiaxial growth is conducted. One possibility is step cooling, in which the melt (at temperature T_0) is rapidly cooled to the temperature of the substrate (T_1) before the two are brought into contact and allowed to cool at a controlled rate. Another possibility is equilibrium cooling, where the melt is brought into contact with a substrate at the same temperature (T_1) and the two are allowed to cool at a controlled rate.

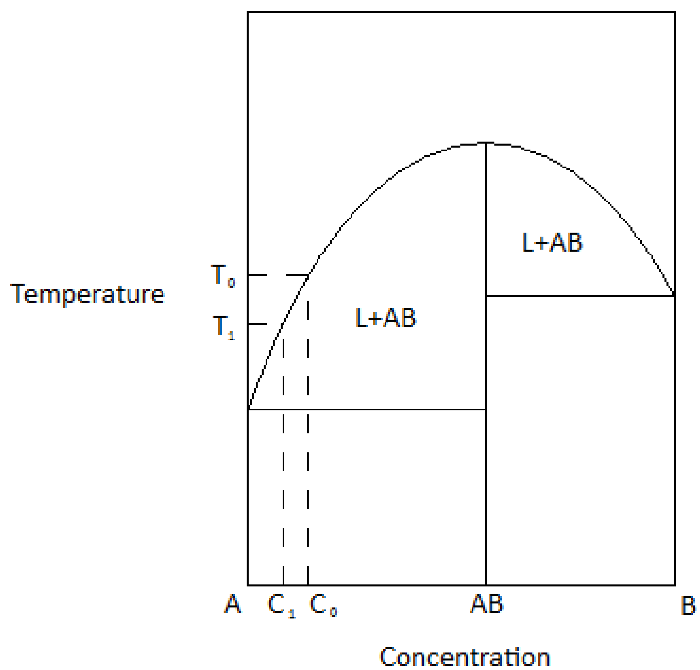

Figure 2: Phase diagram for the A-B system.[1]

Epitaxial layer thickness for step cooling and equilibrium cooling can be calculated by

$$L_{T,SC} = 2\frac{(T_0 - T_1)}{mC_S}\left(\frac{D}{\pi}\right)^{1/2} t^{1/2} \qquad (4)$$

$$m_{SC} = \frac{T_0 - T_1}{C_0 - C_1} \qquad (5)$$

$$L_{T,EC} = \frac{4}{3}\left(\frac{\alpha}{mC_S}\right)\left(\frac{D}{\pi}\right)^{1/2} t^{3/2} \qquad (6)$$

$$m_{EC} = \frac{dT}{dC} \qquad (7)$$

$$\alpha = -\frac{m*[(C(0,t)-C_0]}{t} \qquad (8)$$

where $T_o > T_1$, D is the diffusivity of B in A, C_S is the concentration of B in the solid phase, t is time, and α is the controlled cooling rate. Most often, a controlled layer thickness is desired. Equation 4 provides a relation between layer thickness and temperature, T_1, and time for step cooling; equation 6 relates layer thickness to time for equilibrium cooling.

Diffusion of Dopants into the Metal Oxide Layer

The electrical properties of semiconductors are altered by introduction of n-type (for example, phosphorus, arsenic and antimony) and p-type (for example, boron) dopants that, respectively, increase the number of negative or positive charge carriers. Diffusion of dopants is achieved by two mechanisms, predepositon and drive-in diffusion. Predeposition diffusion maintains a constant surface concentration of the desired dopant while drive-in diffusion has a changing surface concentration of the desired dopant. Fick's second law of diffusion, combined with appropriate boundary conditions for each case, yields the following expressions for dopant dose (Q), the number of dopant atoms per unit area, and junction depth (x_J), the depth where the concentration of the dopant is zero;

$$Q_P = \frac{2C_S}{\sqrt{\pi}}\sqrt{Dt} \qquad (9)$$

$$x_{j,P} = 2\sqrt{Dt} * erfc^{-1}\left(\frac{C_b}{C_S}\right) \qquad (10)$$

$$Q_{DI} = C_S\sqrt{\pi Dt} \qquad (11)$$

$$x_{j,DI} = \left(4Dt * \ln\left(\frac{C_S}{C_b}\right)\right)^{1/2} \qquad (12)$$

where C_S is the surface concentration of the desired dopant, D is the diffusivity of the dopant in the metal oxide layer, t is time, and C_b is the concentration of a background impurity (such as phosphorus or boron) in the metal oxide film.

Depending on the desired electrical properties of the fabricated transistor, engineers dope metal oxide layers to a desired junction depth. Equations 10 and 12 allow engineers to relate the desired junction depth to the surface concentration of the dopant and the time of diffusion.

Conclusion

Chemical engineering contributions to transistor fabrication have made transistors affordable for millions of people globally, thereby assisting in the creation of the internet. Introduction of the internet has spawned major cultural changes, affecting business, job recruitment, education, and social networking. Aside from the internet, wide availability of transistors has advanced information archiving and graphic production. Increases in computational speed have pushed the boundaries of pure and applied research in numerous areas ranging from microbiology to photo voltaic cells. Each cultural change has its associated advantages and disadvantages; it is difficult to say if the changes have been for better or worse. However, change is always with us and, as shown here, chemical engineers will continue to contribute toward influencing cultural changes in many aspects of life.

References

1. Mahajan, Subash, Sree Harsha, K.S., 1999, *Principles of Growth and Processing of Semiconductors*, The McGraw-Hill Companies, Inc., U.S.A.

2. Lojek, Bo, 2007, *History of Semiconductor Engineering*, Springer-Verlag Berlin Heidelberg, Leipzig, Germany.

3. Orton, John, 2004, *The Story of Semiconductors*, Oxford University Press, Inc., New York.

4. Morris, P.R., 1990, *A History of the World Semiconductor Industry*, Peter Peregrinus Ltd., London, United Kingdom.