AC 2003-1050: HIGH-TECH EQUIPMENT SIMULATION

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High-tech equipment simulation

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Abstract

Tools used to fabricate integrated circuits have now reached a level of cost and complexity that are far beyond the capacity of an academic group to acquire or (even if donated) to support adequately. Simulation is an obvious but underused way to provide a broad and realistic environment to demonstrate how the tools work. This paper describes simulation of an ion implanter and simulations for other tools are being developed using the same principles. The control computer emulates all the typical features of a real machine (physical set-up, calibration and operation). In addition, typical faults in the tool can also be introduced. The tool simulator can also be linked to conventional process simulators for virtual lab activities at several course levels.

1. Tools for technology teaching

Any mature commercial technology is intrinsically a complete and well-balanced solution. Microelectronics is a good example where a wide range of skills and disciplines are practiced at a very high level of competency. Design, production and applications interact continuously; technology development is rapid and international competitiveness puts a high premium on a first-class workforce. Arizona has a large semiconductor industry with Intel, Motorola, STM, Microchip, TI, Medtronic, ON Semiconductor and ASML as the leaders. Total employment exceeds 25,000 and more than half have some level of technical qualification. To meet the educational demands for workforce development, an ad hoc partnership of companies and higher education institutions has developed around the Microelectronics Teaching Factory (MTF) at ASU's East campus.

The physical core is the Microelectronics Teaching Factory is a 15,000 sq ft fully facilitized clean room equipped for 150mm wafer processing. Many tools have been donated by local companies - including an i-line stepper, diffusion tubes, plasma etchers and several metrology tools. However, semiconductor processing tools are very expensive to acquire, install and maintain. In the University, we mitigate that cost by operating the MTF as a shared educational resource with very focused programs involving Community Colleges and high schools. Direction and strategy are developed with the aid of a very active Industry Advisory Board.

The academic programs link basic science, engineering design, measurement, data management and control. To this end, simulation is a powerful technique. In particular, simulation of tool operation has many attractions:

- The user interface to most semiconductor process tools is via a computer so a simulator can provide the same interface.
- We can demonstrate many features of tools we do not possess.
- Analogous to a flight simulator, we gain a safe learning environment, ample time for personal learning, emulation of several machine types and fewer real time errors when the transfer to real machines occurs.
- There are many good semiconductor process simulators. They can be linked to the tool operation simulator to give the whole input-output environment.

The purpose of this paper is to demonstrate how a major semiconductor process tool – an ion implanter – can be created in a virtual state and used for mainstream teaching at several levels. The same approach can be used to emulate behavior of other process tools such as oxidation, diffusion and plasma etching. However, we do not see simulation as a substitute for hands-on lab experience with real tools. It can only poorly represent the disciplines of clean and safe working and its scope is very restricted to demonstration of basic tool operation and simplified process outputs. That said, it is a cheap and very flexible educational solution.

2. Ion implantation in the semiconductor process

Semiconductor device fabrication has 3 major components:

1. Layer deposition. The processes by which alternate insulating and conducting layers are deposited on a silicon wafer. The major control criteria are uniformity of composition and thickness.
2. Pattern transfer. The definition of device features by photolithography and subsequent etching to give precise topographical features.
3. Dopant control. Definition of the 3-dimensional dopant distribution in the silicon substrate to determine the electrical characteristics of transistors.

In a modern CMOS process, there are 4 or more implant steps per transistor to provide regions of p-type (boron dopant) or n-type (phosphorus or arsenic dopant) silicon as shown in figure 1. The ion energy defines the depth distribution while the product of beam current and implant time determines the total ion dose [1].

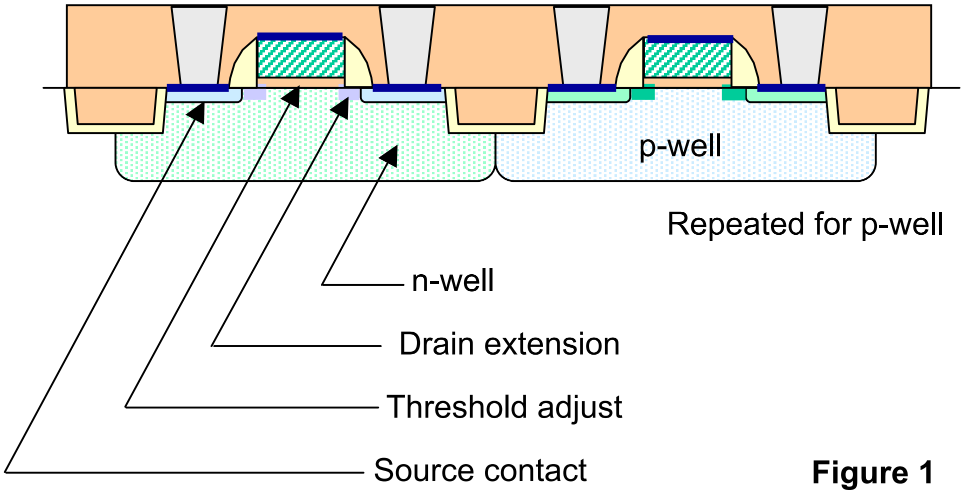


Figure 1

Subsequent thermal processing steps shift the as-implanted profile but the effects can be very adequately simulated [2,3]. If small random variations in process conditions are integrated into the simulation program, sensitivity to the major control parameters, drift and even failure effects can be explored. This is an important attribute of the simulator that is very expensive to demonstrate with a real tool. It also provides an educational platform to study management of variation - one of the key determinants of business competitiveness. There is a natural link to statistical process control and Design of Experiments (DOE).

3. Implant tool simulation

Figure 2 shows a typical ion implantation tool. It is a large machine, typically more than 4 x 3 m with a price tag of $2M or more. The contents and basic functionality are more readily demonstrated by the plan view in figure 3. Since the source may be at >200 kV, substantial safety precautions are in order – interlocks, fiber optic data links, adequate clearance and avoidance of all sharp features that might induce flash-over. With vacuum systems, high voltage supplies, potentially hazardous source materials, automated precision wafer handling, 24 x 7 operation and tight dose uniformity (~ 1%), the high cost of ownership is not surprising.

Figure 2

Applied Materials
Quantum ion implanter

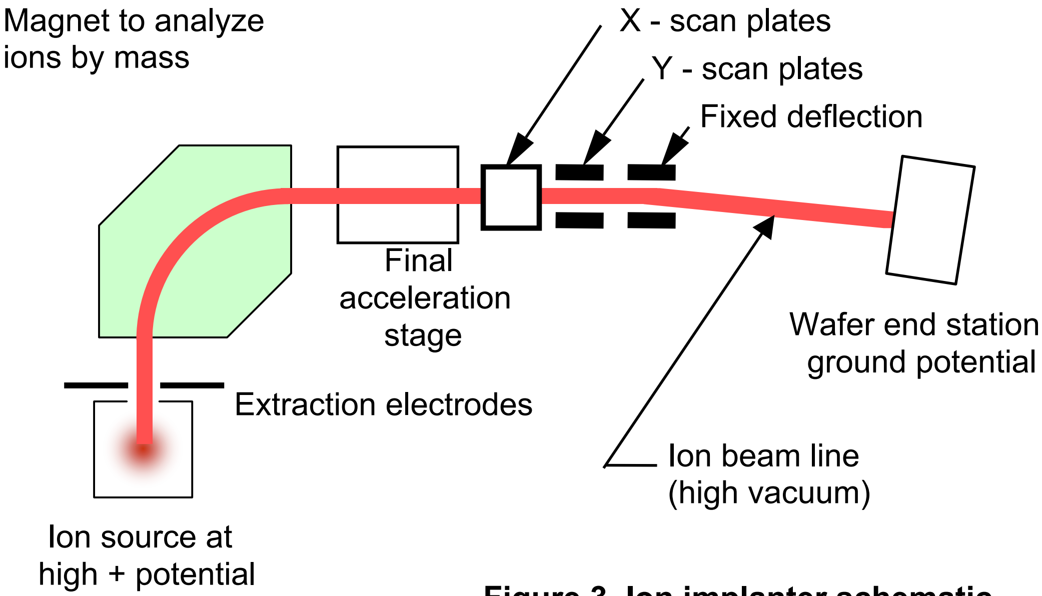


Figure 3 Ion implanter schematic

However, it is a wonderful tool to demonstrate how many basic principles have to be brought together for an effective technology solution. Implantation allows all the major variables to be manipulated independently to achieve desired transistor performance. It is also a good machine to simulate physically. Because of the internal high voltage, the operator sits outside the tool at a computer workstation. By emulating that workstation, the operation of most features of the whole tool can be demonstrated for no more than the cost of a PC and standard software.

The coding was done using MS Visual Basic (VB) 6.0 with Access as the database. The reason for the software selection is that in addition to being a programming language, VB is also an interactive development environment enabling rapid application development. Other advantages include the capability to create a realistic Graphical User Interface (GUI) and easy linking with standard Microsoft Office tools. The principal functions are shown in figure 4.

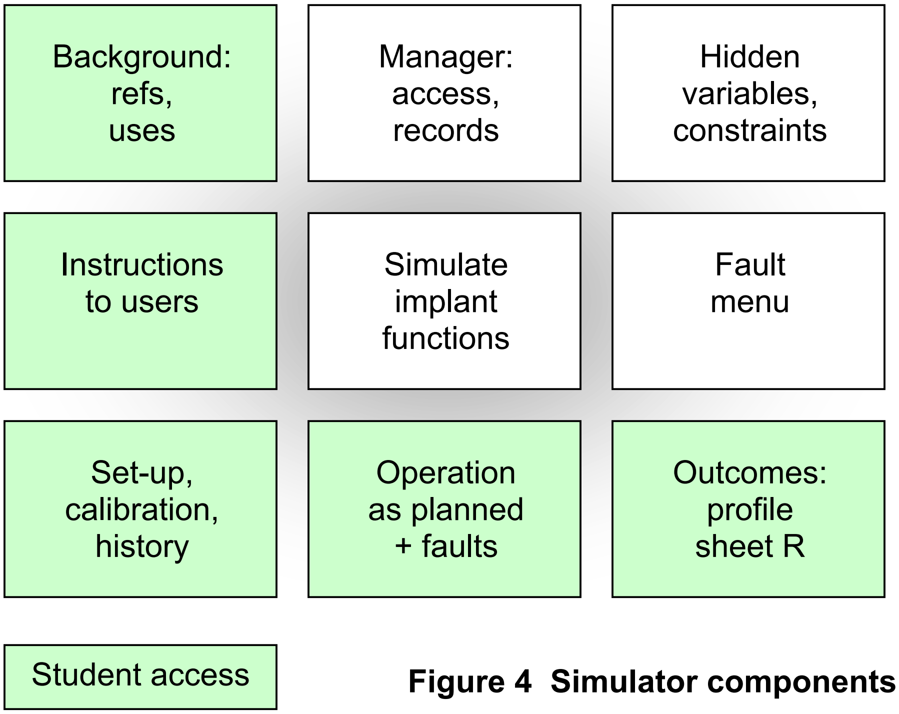


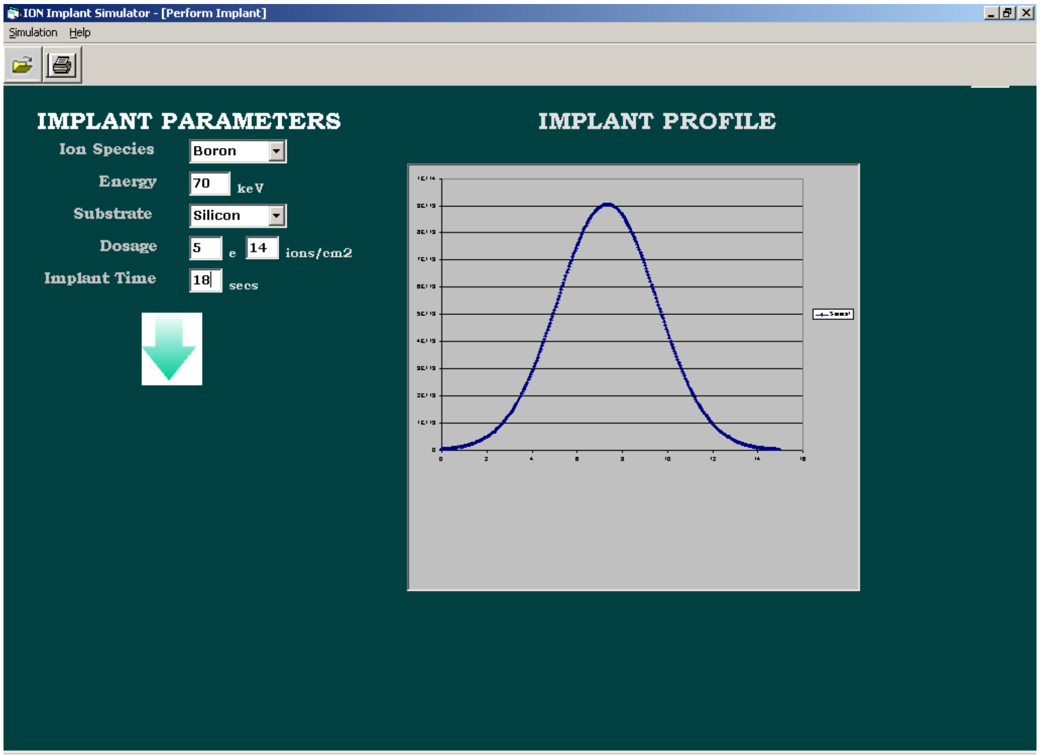
Figure 4 Simulator components

The core of the program is the representation of the major implanter functions:

- Ion source and extraction
- Mass analysis and magnet conditions
- Ion acceleration to maximum potential
- X-Y beam scanning

The program calls up two input files: the student-specified requirements for the experiment and the machine variables that are in a control file. The control file contains all the parameters and constraints used in the governing equations and will eventually be customized to represent specific machine types. In this respect, implantation is one of the better tool functions to simulate since the transfer functions are accurately described by a few equations.

At log-on, the student is presented with a screen that gives the purpose of the activity and the major parameters to be selected. There is a support screen that goes back into the web-based course material for reference and help. Figure 5 and 6 show input screens where the user can input the main parameters for an implant: ion species, substrate material, implant energy, dosage and implant time.



Ion Species: Boron

Energy: 70 keV

Substrate: Silicon

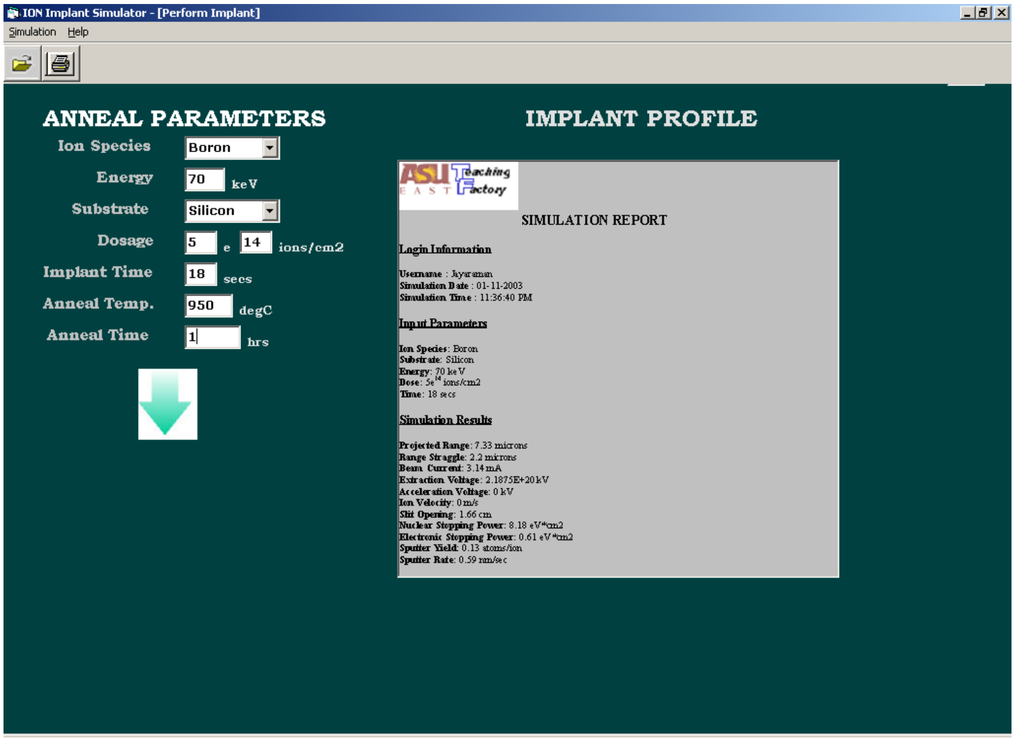
Dosage: 5 e 14 ions/cm2

Implant Time: 18 secs

Figure 5. Implant parameters input screen and generated profile

The program also includes a post-implant anneal function which is activated after an implant has been completed. This module maps the drive-in profile for a user specified temperature and time. The program generates two files – an implant report in MS Word format and the profile as MS Excel chart and stores them in the student's folder.

The program currently only allows implantation of boron, phosphorus and arsenic ions into a silicon substrate. However, it can be further extended to include other ion species and substrate materials.



ANNEAL PARAMETERS

Ion Species: Boron
Energy: 70 keV
Substrate: Silicon
Dosage: 5 e 14 ions/cm2
Implant Time: 18 secs
Anneal Temp.: 950 degC
Anneal Time: 1 hrs

IMPLANT PROFILE

SIMULATION REPORT

Login Information

Username : Jayaraman
Simulation Date : 01-11-2003
Simulation Time : 11:36:40 PM

Input Parameters

Ion Species: Boron
Substrate: Silicon
Energy: 70 keV
Dose: $5e^{14}$ ions/cm2
Time: 18 secs

Simulation Results

Projected Range: 7.33 microns
Range Straggle: 2.2 microns
Beam Current: 3.14 mA
Extraction Voltage: 2.1875E+20 kV
Acceleration Voltage: 0 kV
Ion Velocity: 0 m/s
Slit Opening: 1.66 cm
Nuclear Stopping Power: 8.18 eV*cm2
Electronic Stopping Power: 0.61 eV*cm2
Sputter Yield: 0.13 atoms/ion
Sputter Rate: 0.59 nm/sec

Figure 6. Anneal parameters input screen and view of simulation report.

The manager file is password protected and has overall control of all operations. It establishes a file for each student to record the experimental conditions chosen and the results. The file is available as a report for the student at the end of the experiment. However, it can also be combined with other student results to build up a DOE matrix as an overall class experiment. The manager can also select faults from a menu to be added to the operational conditions. The current fault list includes:

- Contamination as a result of source change
- Poor ion extraction efficiency
- Variation in magnetic field giving an asymmetrical beam shape
- Dispersion in ion energy
- Effects of poor vacuum and ion neutralization
- Raster scan 'beating'

At present, these fault conditions are based on straightforward variations of input conditions. However, the goal is to link the menu to real-world experience and reflect the typical incidence of faults. This contribution will come from our industry advisors.

4. Applications and conclusions

Currently, the MTF does not possess an ion implanter. If we need implantation for device fabrication, it is more cost effective to buy the service. However, implantation is a vital part of an integrated semiconductor process curriculum [4] so the ownership of a virtual machine fills a big educational gap. So far, the program has only been used in class demonstrations with BSET students. The next stage is to integrate it into the web-based preparation for the dopant control course. It will also be released to community college faculty involved in our partnership program [5].

The Visual Basic implementation was adequate for a prototype in a fully prepared computer environment. However, it is not a robust solution for widespread distribution where it encounters different PC and operating system generations. The reasons are software availability and version compatibility. A simpler alternative could be to implement the program in its entirety using MS Excel. Although it will give a slower response, it will be well within the execution time for a real machine. We can also more readily incorporate status indicators, diagnostic messages and other typical machine GUI features.

References

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Bios

JOHN ROBERTSON is a professor at ASU's East campus in Mesa, Arizona. From 1993 to 2001, he held a number of senior R & D positions in Motorola's Semiconductor Products Sector. His earlier academic experience was as Lothian Professor of Microelectronics in Edinburgh University, UK where he managed a national research center with interests in process control and the global economics of high-technology.

SIVAKUMAR VENKATANARAYANAN is a graduate student in Electrical Engineering Technology at ASU. His specialization is Microelectronics, focusing on the CMOS process flow. He is currently working on his Master's thesis under Dr. John Robertson on a simulator for a generic medium current ion implanter. He has a Bachelor's Degree in Engineering from the University of Madras, Chennai, India.