Modeling Wafer Temperatures Using the MD Marc Welding Capability

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Abstract. Ion implantation into silicon wafers results in heat buildup in the wafers during the manufacture of integrated circuits. The wafers are subjected to an ion beam that rasters over the surface of the wafer. A two-dimensional scan is necessary to uniformly implant the surface of the wafer. The ion beam is scanned across the wafer at frequencies of 1-1000 Hz. The vertical scan is typically much slower, with frequencies that are <1 Hz. The Marc welding capability was successfully used to model the motion of the ion beam heat source over the surface of the wafer. The model itself was built using the Patran interface, and then exported to Marc for analysis. After the text file was written out, it could be simply edited to change the parameters of the problem, including wafer diameter, beam diameter, beam power, beam velocity, and wafer backside cooling.

Keywords: moving heat source, wafer temperature, ion implant

INTRODUCTION

The manufacture of integrated circuits (IC) requires the implantation of ions, such as phosphorus (P), boron (B), arsenic (As), and hydrogen (H), into crystalline wafer substrates, such as silicon (Si) and germanium (Ge). The residual heat from the implant process can damage the electronic devices which are being manufactured on and within the wafer, resulting in a low device yield. Temperatures as low as 100°C can cause deterioration of the photoresist (PR) masks which are commonly used in the manufacture of IC's. Also, wafer heating can cause an amorphous layer to form in the otherwise crystalline wafer, which adversely affects the semiconductor properties of the wafer. When temperatures reach 600°C, there can be slippage of crystal lattice planes [1]. Therefore it is imperative to control wafer temperature.

In previous generations of implanter design, the wafers are processed in "batch" mode, where up to 13 wafers are mounted on the outer region of a conical, spinning disk [2]. These batch wafers are held on the disk by "inertial clamping" produced by the inverse conical shape of the disk, which spins at about 1200 RPM. The tangential motion of the spinning disk produces the "fast scan" part of the implant, while the slower, translating motion of the disk assembly produces the "slow scan" part of the implant.

In the newer generation of ion implanters, the wafers are processed one-at-a-time, known as serial implanting. During the ion implant process, the wafer is held by a platen, typically an electrostatic clamp (ESC). The fast scan part of the implant is usually done by means of an electrostatic scanner, which scans the ion beam at frequencies on the order of 1000 Hz. In some types of implants, such as in high-current implanting, the ion beam is more easily scanned mechanically, where the wafer/platen assembly oscillates through the path of the ion beam at frequencies up to 5 Hz. The slow scan part of the implant is done by mechanically translating the wafer/platen assembly.

Wafer cooling in any implanter design is problematic because the interior of the process chambers are kept at high vacuum (figure 1). Therefore the only practical method of heat removal from the wafer is through backside cooling. Two methods of backside cooling

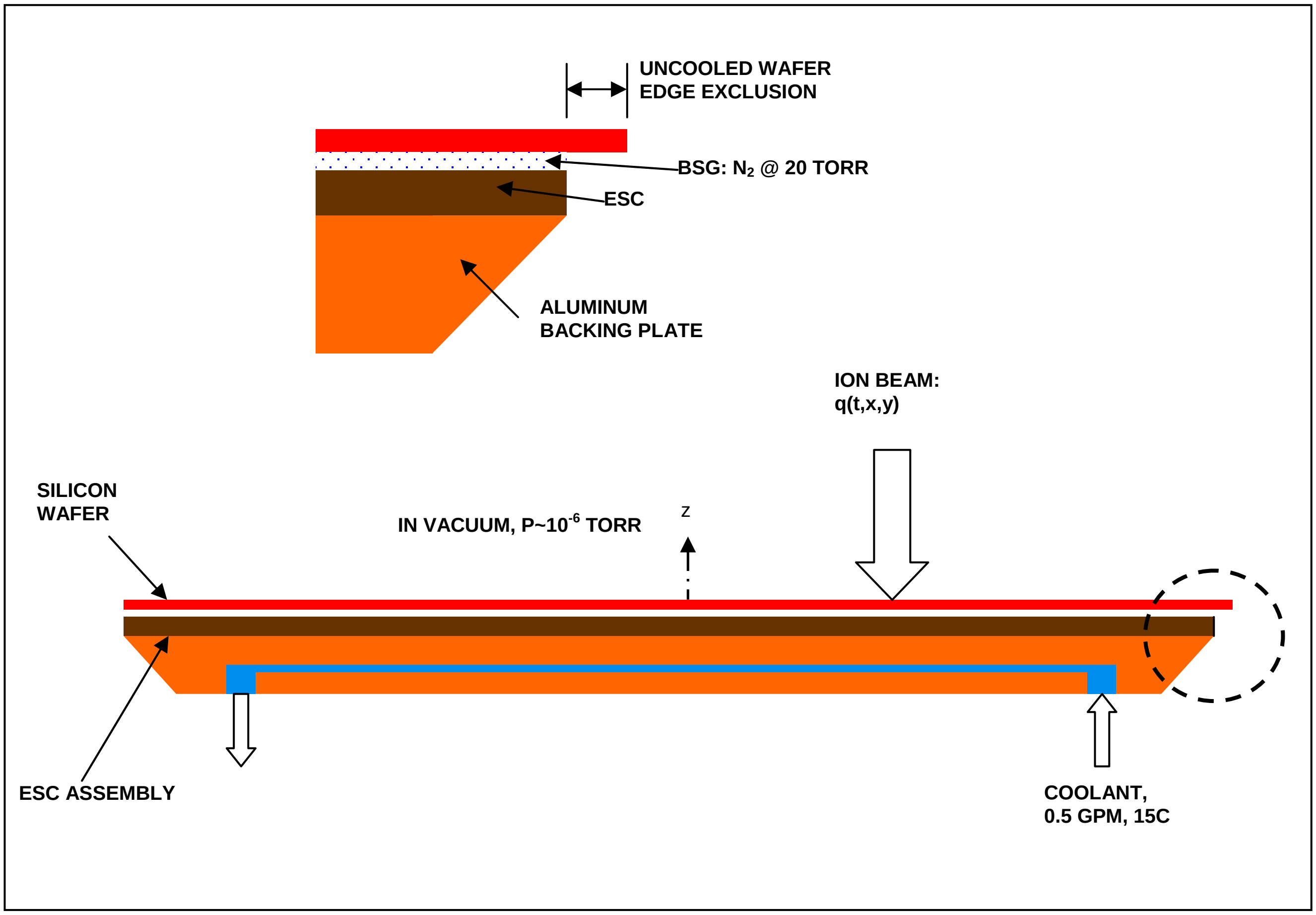

FIGURE 1. Layout of wafer and electrostatic clamp (ESC) platen. Backside gas (BSG) at low pressure, about 20 torr, is used between the wafer backside and platen to remove heat from the wafer. The heat is eventually removed from the platen by flowing coolant through the platen.

Scan Type	***X-Direction*** **Scan Speed (cm/s)**	***Y-Direction*** **Slow Scan Speed (cm/s)**	**Ion Beam Size D (cm)**	**X-Direction Fast Scan Limit L (<<1 for 1D simplification)**	**Fast Scan Limit Exceeded?**
Fast X-Direction / Slow Y-Direction	**~5000**	**~10**	**~1**	**1E-5**	**No (can be modeled as 1-D moving rectangle)**
Slow X-Direction / Slow Y-Direction	**~6**	**~0.6**	**~8**	**0.07**	**Marginal**

TABLE 1. Implant parameters and resulting fast scan limit for two scan types. The fast X-direction scans are produced by spinning disks or by electrostatic scanners. Mechanical scanning occurs at much slower speeds, in the range of $0.5 \leq V_{ms} \leq 100$ cm/sec.

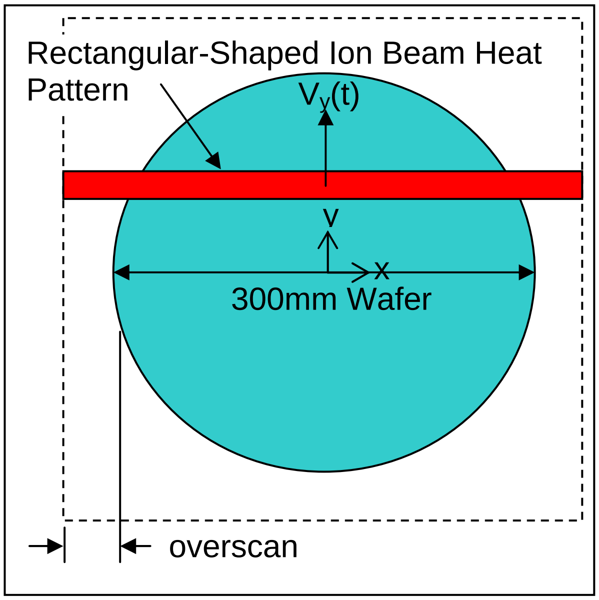

FIGURE 2. Scan layout for ion beam that moves slowly in 'y' scan direction but "fast" in the 'x' scan direction. Speed only depends on vertical position 'y.' The rectangular ion beam is modeled using option 3 in the weld flux type of the weld flux command in conjunction with a user-defined subroutine that defines the rectangular profile.

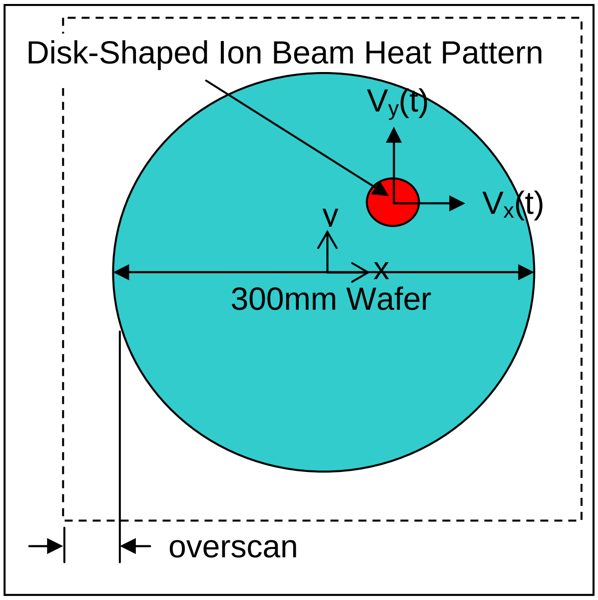

FIGURE 3. Scan layout for ion beam that moves slowly in both scan directions. Over scan distance is at least the diameter of the ion beam. The ion beam is readily modeled as "Pavelic's" disk using option 2 in the weld flux type of the weld flux command.

are (1) contact cooling on an elastomeric pad and (2) backside gas (BSG) cooling using a low-pressure gas which is introduced between the wafer backside and the platen. The BSG pressure is typically at about 20 torr, where the gas is typically nitrogen, argon, or helium. BSG cooling produces a cooling coefficient of about 70 mW/cm^2-°C, whereas contact cooling with an elastomeric pad surface produces only about 15 mW/cm^2-°C. This is the primary reason why BSG cooling has become the preferred method of controlling wafer temperature within the implanter industry.

PROBLEM DEFINITION

Ion Beam Power

The heat that is produced by ion beams during the implant process is expressed, in watts, as

$$P = VI \tag{1}$$

where V is the beam energy in electron-volts and I is the beam current in amperes. The shape of the beam cross-section is roughly equivalent to a disk or ellipse, but the exact shape is very dependent on the beam tuning conditions that are upstream of the wafer. The power density of the beam cross-section is approximately Gaussian.

Modeling the Fast X-Scan

In the case of an implant having a fast x-direction speed, then the ion beam may be approximated by a rectangular "ribbon" beam that only scans in the remaining direction (figure 2). The criterion for treating the fast scan as a ribbon is called the "fast scan limit" and is designated here as **`L`**. The derivation of `L` is presented in appendix I. Essentially, `L` is the ratio of the pulse width of the ion beam and wafer thermal time constant. In order for the ribbon approximation to be valid, then `L` << 1 for the ion beam being considered.

For the fast x-direction scan, having a speed of ~5000 cm/sec and a beam diameter of ~1 cm, the resulting limit is `L` = 1E-5. Thus the electrostatically scanned beam can be modeled as a ribbon of height D and a width which is equal to the scanned area width and that oscillates vertically at 10 cm/sec. The height and width of the scanned area include a region of over scan. The over scan distance is generally at least the size of the beam. Over scanning is generally required to maintain uniformity of the implant across the wafer surface.

The present study required writing a FORTRAN subroutine that is called by the weld flux command as weld flux type 3 in Marc. The subroutine defines the height, width, and power of the ion beam (appendix II).

Modeling the Slow X-Scan

For the case of a mechanically scanned x-direction ion beam, the beam speed is ~6 cm/sec and the beam diameter is ~8 cm. This gives a limit of L = 0.07. In this case it is not clear whether the criterion has been satisfied. As such, the mechanically scanned x-direction beam should be modeled as a "dot." This aspect lends itself well to the welding capability in Marc, which assumes a "Pavelic's" heat distribution in the case of a disk [3]

RESULTS

For the case of the implant having fast x-direction speed and slow y-direction speed, the temperatures were highest at the edges of the wafer (figure 4). This result is due to the uncooled edge of the wafer, which is 7.5mm, and to the fact that a point at the edge has about half of the conduction area as a point in the interior of the wafer. The wafer temperature was actually highest at the top and bottom edges of the wafer, where the ion beam moves off of the wafer surface into the over scan region, stops, then quickly returns to begin the next scan. This creates a typical double peak at these edges of the wafer, producing the highest temperatures in the wafer [5].

In the case of the implant having slow x-direction and slow y-direction speeds, the temperatures were also highest at the edges of the wafer (figure 5). Though the edge exclusion zone was only 3.5mm in this case, the edge effect on temperatures occurs for the same reasons as in the previous case. The effect of modeling both directions of scan can be seen in the results. The temperature peaks which are produced by the x-direction scan are basically superimposed on the broader peaks which are produced by the slower moving y-direction scan. These peaks are at least 25% higher than the peaks that would have been predicted using only a 1-D scan. Thus it appears that there is much benefit in modeling the full, 2-D scan.

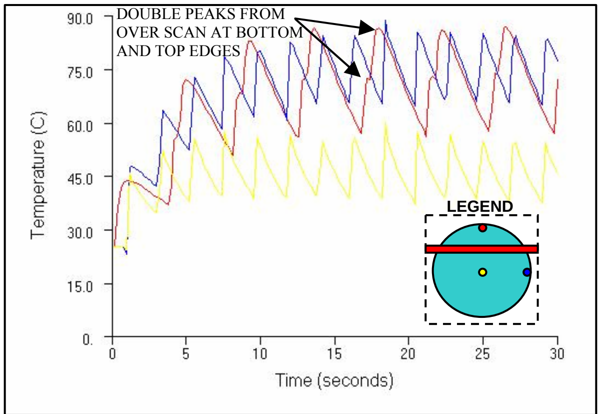

FIGURE 4. Wafer temperature profiles for the case of a fast scan speed in the x-direction and slow scan speed in the y-direction. Implant parameters are Q=1.5kW, V=19cm/s, H=2.5cm, and edge exclusion=7.5mm.

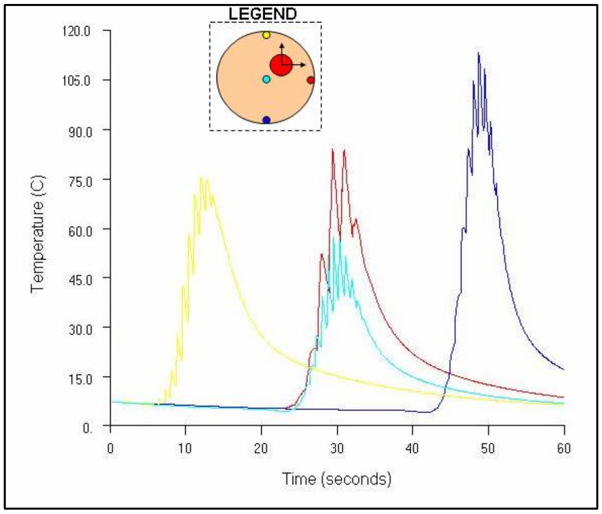

FIGURE 5. Wafer temperature profiles for the case of slow scan speeds in both directions. Implant parameters are Q=1.0 kW, V_x=60 cm/s, V_y=0.8 cm/s, D= 6 cm, and wafer edge exclusion=3.5mm.

CONCLUSIONS

The wafer temperatures that occur as a result of ion implanting were successfully modeled using Marc and its welding capability. We were able to model two types of implants, one with a slow scan in the vertical, or 'y' direction, and fast scan in the horizontal, or 'x' direction, and the other with a slow scan in the vertical, or 'y' direction, and slow scan in the horizontal, or 'x' direction. We tested the "fast scan limit" theory of modeling beam scans. The result was that it was beneficial, probably in all cases, to model the implant as a 2-dimensional scan. The 2-D scan showed that the lateral component of temperatures added roughly 25% to the same temperature profiles that were produced using only a 1-D scan.

APPENDIX I: FAST SCAN LIMIT

Following the reasoning of Mack [4], we can deduce the “fast scan limit” of the wafer and ion beam. The fast scan limit is the criterion that determines whether the ion beam can be modeled as a rectangle whose velocity is one-dimensional. The value of this approximation, when it is valid, is that the solution computation of the thermal problem is simpler.

The time constant of the cooled wafer is

$$\tau = \frac{\rho L C_p}{h} \tag{1}$$

where ρ is the density of silicon, 2.33 gm/cm^3, L is the thickness of the wafer, 0.775 mm (for a 300mm diameter wafer), C_p is the heat capacity of silicon, 0.75 Joules/gm-°C, and h is the heat-transfer coefficient between the wafer and the platen. For BSG cooling, $h \approx 70$ mW/cm^2-°**C** for nitrogen at a pressure of 20 torr of the backside gas, typically. Using these values, the wafer thermal time constant is $\tau = 1.9$ seconds.

The time duration of the heat pulse which is experienced by a point on the wafer as the ion beam passes over the point is

$$t = \frac{D}{V} \tag{2}$$

where D is the average diameter of the ion beam and V is its velocity (see table 1).

In order for the ion beam to be modeled as a rectangle, (i.e. the fast scan limit has not been exceeded) it is necessary that the duration of the heat pulse t be much shorter than the wafer time constant τ. This can be stated as:

$$\boldsymbol{t \ll \tau} \tag{3}$$

Combining eqs.1 and 2, the result is

$$\frac{D}{V}\frac{h}{\rho L C_p} \ll 1 \tag{4}$$

For convenience, we will name the left side of eq.4 the fast scan limit, or `L`. Then the fast scan limit is

$$\mathtt{L \ll 1} \tag{5}$$

APPENDIX II: MARC SUBROUTINE FOR RECTANGULAR BEAM SHAPE

```
      subroutine uweldflux(f,temflu,mibody,welddim,time)
      include '../common/implicit'
      dimension mibody(*),temflu(*),welddim(*)
c* * * * * *
c
c     user subroutine for weld flux input.
c
c     f              weld flux value (to be defined)
c     temflu(1,2,3)  local integration point coordinates (wrt weld origin)
c     temflu(4,5,6)  global integration point coordinates
c     mibody(1)      element number
c     mibody(2)      distributed flux type
c     mibody(3)      integration point number
c     mibody(4)      weld flux index
c     welddim(1)     weld width
c     welddim(2)     weld depth
c     welddim(3)     weld forward length
c     welddim(4)     weld rear length
c     time           time at end of incement
c
c     INPUT:         temflu,mibody,welddim,time
c     OUTPUT:        f
c* * * * * *
!-------------------------------------------------
!
!  SUBROUTINE OVERVIEW:
!    This user subroutine calculates the heat flux at a given location for a
!    simple rectangular shape with a uniform heat flux within the rectangle.
!    The weld location is the center of the rectangle.
!
!  INPUT:
!    3 variables are used for this example.
!      rectangle_width  = the width of the beam
!      rectangle_height = the height (in direction of the beam)
!      beam_power   = the nominal heat power of the ion beam
!
!
!
!
!
!  Subroutine variables
      REAL*8 f, temflu, welddim, time ,beam_power
      INTEGER mibody

      REAL*8 rectangle_width, rectangle_height
      REAL*8 rectangle_flux
      INTEGER weld_flux_index

!  Variables entered by user
      weld_flux_index  = 1
      rectangle_width  = 460
```

```
 rectangle_height = 40
   beam_power = 4000
 rectangle_flux   = beam_power/(rectangle_width*rectangle_height)

 if( ( mibody(4).eq.weld_flux_index ) .and.
& ( abs(temflu(3)).le.(rectangle_height/2.0) ) .and.
& ( abs(temflu(1)).le.(rectangle_width/2.0)) ) then
   f = rectangle_flux
 else
   f = 0.0
 endif

 return
 end
```

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