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Study of the thermal effect on silicon surface induced by ion beam from plasma focus device

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ABSTRACT

Structural modifications in form of ripples and cracks are induced by nitrogen ions from plasma focus on silicon surface. The investigation of such structures reveals correlation between ripples and cracks formation in peripheral region of the melt spot. The reason of such correlation and structure formation is explained as result of thermal effect. Melting and resolidification of the center of irradiated area occur within one micro second of time. This is supported by a numerical simulation used to investigate the thermal effect induced by the plasma focus ion beams on the silicon surface. This simulation provides information about the temperature profile as well as the dynamic of the thermal propagation in depth and lateral directions. In accordance with the experimental observations, that ripples are formed in latter stage after the arrival of last ion, the simulation shows that the thermal relaxation takes place in few microseconds after the end of the ion beam arrival. Additionally, the dependency of thermal propagation and relaxation on the distance of the silicon surface from the anode is presented.

1. Introduction

Plasma Focus (PF) has been widely used as a rich ion source for various material science applications [1–14]. It is a source of ion beams with high energies and flux. The high plasma ion flux rises the temperature of the target within a short time. The deposited energy on the target surface depends of the number and energy carried by the ions. The PF can produce ions with high energy from few keV up to MeV. The maximum ion flux (of about 1.86×10^{17} - ions/sterad) is obtained for ions of lower energies (tens of keV) while minimum ion flux is obtained for ions of higher energies. The ion energy flux is associated with the focusing efficiency of plasma focus device as well as the working gas pressures [15–17].

Sanchez et al. [18,19] have investigated the thermal effect of ion implantation into pure titanium, stainless steel and copper using ultra-short duration ion beams generated by the plasma focus. The temperature profiles and their evolution during and after nitrogen ions implantation were studied by finite difference method. The implantation ofnitrogen ions (fluence of $10^{13}\ cm^{-2}$ and pulse time of *400 ns*) in pure titanium showed a melting layer of 20 nm after the first *200 ns* of implantation, followed by a fast cooling rate. M. Hassan, et al. [20], reported that the temperature of the top layer of the titanium surface rises to about 5400 K under the plasma ions bombardment.

From other side, there are experimental observations of the thermal effect on the surfaces exposed to PF ions. Among these observations, the formation of micro and nanopores in Si surface which are distributed in the center and peripheral regions of the irradiated area, respectively [21]. This distribution is a consequence of the implication of melting and liquid-phase process induced by the energy of ions deposited in the Si surface. M. Ahmad et al. [22] observed the formation of nano and microspheres in the deposition of bismuth over Si. The spheres formation and distribution are due to the implication of thermal effect. The size of spheres and the formation of comet–like structures are dependent on the temperature gradient beneath the deposited bismuth. Ion beam bombardment under oblique incidence is used to induce nanostructures in form of wave-like ripples on solid surfaces [23]. The formation of ripple patterns using ion beam sputtering (IBS) has been known and studied experimentally [24] and theoretically [25] for some decades. Such rippled structure is observed by plasma focus [26,27]. A similar observation called tubular structure is observed by [28]. Ripples can be seen in figures presented by [29]. However, the reason of such structure

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formation by PF has not been a subject of interest as done by ion beam sputtering [23–25].

In this work, AECS PF1 as a plasma focus device is used to induce and study morphological change and structural formation which are influenced by the thermal effect of plasma ions on the Si surface. Additionally, the experimental observation of the thermal effect is explained in base of a simulation model results. This simulation deals with the thermal evolution of the surface layers of silicon during and after nitrogen ion beam irradiation, using the heat diffusion equation solved by the finite-difference method.

2. Experimental details

The same experimental plasma setup and conditions taken in [21,22] are used in this present work. Briefly, the plasma focus device (AECS PF1) is a low energy (2.8 kJ) Mather-type, equipped with a solid cylindrical anode made of copper. The diameter and length of the anode are 19 mm and 160 mm, respectively. The PF discharge was operated in nitrogen gas at pressure of 0.6 mbar. Intrinsic silicon (1 1 1) substrates were mounted above and in the axis of the anode. Some silicon samples are treated at different experimental conditions like: number of plasma shots and different distances from the top of the anode. A TESCAN VIGA II XMU Scanning Electron Microscope (SEM) is used in order to study the surface morphology of the PF treated silicon.

3. Numerical simulation of thermal effect of ion beam plasma focus

Direct measurements of the target's thermal evolution under PF ion implantation is very difficult task from a technological point of view. Computer simulation can help in performing this task. In this work the thermal effect is studied using numerical calculations based on the PF ion beam characteristics, ion–solid interactions and the thermal properties of matter. The results of the calculations are compared with some experimental results on the 2.8 kJ AECS PF1 device.

3.1. Ion beam modeling

The energy delivered to the target is a function of the ion number and the energy distribution. The range of ion energy can be taken in the interval between 20 keV and 500 keV. The number of ions N with energy E is given by [18]:

$$N(E) = \frac{\alpha}{2.5}\left(5.59 \times 10^{-4} - E^{-2.5}\right) \tag{1}$$

where α is a constant of proportionality. This relation can be inverted as:

$$E(N) = \left(5.59 \times 10^{-4} - \frac{2.5}{\alpha}N(E)\right)^{-0.4} \tag{2}$$

To perform the numeric calculation, it is necessary to discretize the continuous variables N and E partitioning the energy interval in subintervals of length ΔE. The ith energy subinterval is in the range between E_i and $E_{i+1} = E_i + \Delta E$. The corresponding energy fluence in such a subinterval becomes

$$\varepsilon_i = \frac{1}{\sigma}\int_{N(E_i)}^{N(E_{i+1})} E(N)dN \tag{3}$$

where σ is the ion beam cross section at a distance l from the focus. In this case, and considering the beam has a conical geometry, it can be calculated as $\sigma = \pi(l\tan(20))^2$. Considering ions from the energy interval (E_i, E_{i+1}), the first ion of such an interval to arrive at the target will be one with energy E_{i+1} and accelerated at $t = 0$, and the last, one with energy E_i and accelerated at $t = 200$ ns. The ions of the ith energy subinterval will interact with the target in a lapse $\Delta\tau_i = \tau_i - \tau_{i+1}$ where $\tau_i = l\sqrt{\frac{m}{2E_i}}$ and m is the ion mass.

The energy per time and area unit delivered at the target by the ions of the ith subinterval can be obtained as $\xi_i = \frac{\varepsilon_i}{\Delta\tau_i}$.

When the ion penetrates into the target it loses energy by collisions until it stops at a certain depth below the target surface. This depth is called the projected range R_p and it depends on the ion mass, ion energy and target nature and density.

In this work, the energy transform from the ion beam to the target is considered as an energy flux released in layers, of thickness defined by R_p, below the surface. It is assumed for simplicity that the whole kinetic energy of the ion is transformed into thermal energy into the bulk of the target. The range R_p for each particular situation and for each ion energy was calculated using the TRIM code [30]. For ions with energy in the ith subinterval a mean projected range R_{pi} can be defined. The energy per time and volume unit delivered by the ions of the ith energy subinterval into the target can be obtained through the equation: $\dot{q}_i = \frac{\xi_i}{R_{pi}}$. A point at any depth d into the target will receive energy from the ions with $R_p \geq d$. The energy flux delivered by the ion beam into that point is: $Q = \sum_i \dot{q}_i$. The summation is extended over all i that satisfy the condition $R_{pi} \geq d$.

3.2. Thermal evolution of the target

When energy is delivered to regions of dimensions much greater than the heat diffusion length in material bulk and convection currents can be ignored, one-dimensional diffusion equation [18]:

$$\frac{\partial^2 T}{\partial x^2} + \frac{Q}{k} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{4}$$

may be used to calculate thermal evolution of an implanted target. In Eq. (4) T is the temperature, Q the energy flux, x denotes the variable depth in the target, t is the time, k is the thermal conductivity and a is the thermal diffusivity of the material.

Heat convection equation can be solved analytically or numerically. The analytical solution is almost impossible in the case of multi-layer systems, in which phase transitions take place and thermal parameters are temperature-dependent.

In this paper the finite-difference method is applied in the resolution of Eq. (4). To implement this method the spatial and temporal domains are divided in small subdomains of length Δx and Δt. One node is assigned to each spatial subdomain, Δx being the distance between nodes and w the total number of nodes.

The boundary conditions must be specified at each boundary point. In our simulations two edge conditions were necessary. The first condition is that the energy flux absorbed at the surface is totally converted into heat as described in previous subsection. The second boundary condition is that temperature at the backside of the target is close to the ambient temperature at all times. Under energy deposition, the temperature of any given ith element within the target rises up until it reaches the melting point, subsequent energy deposited within that element is accumulated until the value corresponding to the latent heat is reached. Thermodynamic parameters for liquid phase of the material involved are used for the period the element remains molten. Solidification is taken into account in a similar manner. MATLAB program is used in the calculation, results are returned in a two-dimensional matrix, which contain data necessary to determine temperature profile within the target after each time interval, the melt duration, and the maximum melt depth.