COMPARATIVE ANALYSIS OF ION AND LASER PULSE ANNEALING OF SILICON

Yu. A. Bumai, N. E. Domorod, and A. G. Ul'yashin

UDC 539.12.04

We present results from the modeling of silicon heating with an ion or laser pulse of 10^{-6}-10^{-7} sec duration. The model is used to describe ion pulse alloying in the self-annealing regime and in laser annealing.

A promising method to produce alloyed semiconductor materials for micro- and opto-electronics involves ion pulse alloying in the self-annealing regime. It is reported in the review presented in [1] that promising results have been obtained through the application of this method to produce n^+—p diodes and solar batteries, synthesis of crystalline silicon carbide layers on silicon, and the attainment of silicon-insulation structures. In this connection, the mathematical modeling of ion pulse processes has become urgent, since it would allow us to find optimum regimes for the production of materials exhibiting the required characteristics. A comparison of results from the modeling of thermophysical processes in ion and laser pulses of identical duration (10^{-6}-10^{-7}) and pulse shape is covered in this study.

The model for the heating of a solid semiconductor by ion or laser beams, in which consideration has been given to the melting of the surface layer and its subsequent crystallization, has been described in [2] and it is a one-dimensional equation of heat conduction for a solid-melt system without explicit identification of the boundary of phase separation:

$$\rho\,[c(T)+L\delta(T-T^*)]\,\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[K(T)\,\frac{\partial T}{\partial x}\right]+Z(E,\ t,\ x),$$

where $Z(E,t,x) = f(t)P(E,x)$ is the source of heat for the ion (laser) beam; $f(t)$ is the time form of the pulse. The irradiated specimen surface ($x = 0$) is assumed to be heat insulated: $\partial T(0, t)/\partial x = 0$ (the adiabatic regime). At a distance d from the surface (deep within the specimen) the temperature is assumed to be constant: $T(d, t) = 300$ K. Calculation has shown that at $d \gtrsim 0.05$ mm its value does not affect temperature distribution. For the laser beam

$$P(\lambda,\ x)=(1-R)\,Q\exp[-\alpha(\lambda)\,x].$$

For the ion beam the form of the energy-release function $P(E, x)$ depends on the mechanisms of ion energy loss which predominate. For light ions with energies of $\sim 10^1$-10^2 keV the primary mechanism for energy loss may be assumed to be electron deceleration [3]. The spatial distribution of the energy liberated into the electron subsystem as a result of inelastic interaction was held to be symmetrical (Gaussian) and described by two initially important quantities, i.e., the average depth R_{PI} and mean-square scatter ΔR_{PI} [3]. Then, for a monoenergetic beam

$$P(E,\ x)=\frac{Q}{\sqrt{2\pi}\,\Delta R_{PI}}\exp\left[-\frac{(x-R_{PI})^2}{2\Delta R_{PI}^2}\right].$$

For the time form of the pulse we used the expression

$$f(t)=\begin{cases}[1+\cos(2\pi t/\tau)]/\tau, & 0\leqslant t\leqslant\tau,\\ 0, & t>\tau.\end{cases}$$

The equation was solved by a grid method based on a purely implicit discretization scheme. Such a scheme is absolutely stable and monotonic, thus making it possible to achieve a solution with relatively large time intervals ($\Delta t = 0.1$ nsec). The δ function was approximated by the expression: $\delta(T-T^*) \to [1-\cos\pi(T-T^*)/\Delta]/2\Delta$ for $|T-T^*| < \Delta$, normalized to 1. Here Δ represents the smoothing interval.

The calculations were carried out for beams of p^+ protons, and for B^+, Al^+, P^+, and As^+ ions with energies of 60, 100, 150, 200, and 300 keV at a pulse duration of 140 nsec and with an energy of 5 keV for a duration of 1 μsec, as well as for a laser pulse of the same duration, with a wavelength of 0.69 μm. The calculations for pulses of Gaussian and rectangular shape with identical energy density, showed that the effect of pulse shape on the results of the ion (laser) beams (depth of melt and time of existence)

Belorussian Polytechnic Institute, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 60, No. 3, pp. 494-498, March, 1991. Original article submitted February 14, 1990.

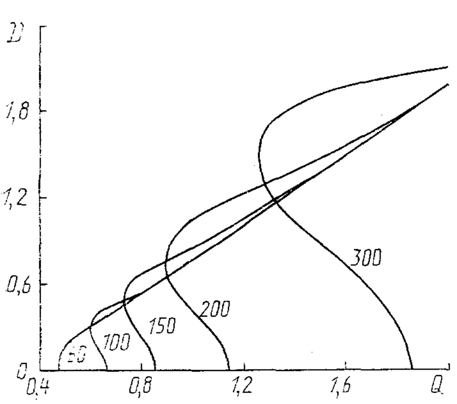

Fig. 1

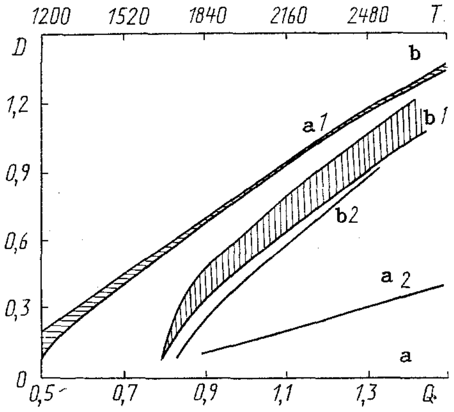

Fig. 2

Fig. 1. Extreme positions of the boundary of phase separation between the crystalline silicon and the melt as a function of the density of the incident energy in a proton pulse (140 nsec, 60-300 keV). D, μm; Q, J/cm^3.

Fig. 2. Maximum thickness of the recrystallized layer as a function of the density of the incident energy (a) and as a function of surface temperature (b) in a proton pulse of B^+, Al^+, P^+, and As^+ (60-200 keV) (1) and in a laser pulse (2) lasting 140 nsec. (For ions of the form and energy indicated here, the results differ insignificantly, and instead of individual curves in close proximity to each other we show cross-hatched regions a1 and b1, containing these curves.) T, K.

is inconsequential under these conditions (it does not exceed several percent).

From the calculation results we can see that a change in the density of the energy in the beam within limits of 0.5-1.5 J/cm^3 and an average ion energy can result in crystalline alloying of a silicon layer with a thickness of less than ~1 μm and an implantation dose of ~10^{13}-10^{14} cm^{-2}. The impurity concentration in the recrystallized layer reaches ~10^{17}-10^{18} cm^{-3} in this case. With microsecond ion annealing the thickness of the recrystallized layer reaches 2 μm for an implantation dose of ~10^{15} cm^{-2}. For this we require ion pulse sources with a current density of ~10^1-10^2 A/cm^2 [4, 5].

Estimates for the velocity of motion in the crystallization front show that it does not exceed ~3 m/sec, and in the melt layer it becomes possible to restore the crystalline structure as the alloying impurity is distributed through the depth (determining the profile of such a distribution requires the joint solution of the equation of diffusion and the equation of heat conduction, in conjunction with the segregational effects, all of which is beyond the scope of the present study; if the thickness of the melt is greater than the average projected mean free path of the ions in the substance, in estimating the impurity concentration in the recrystallized layer we may assume that the impurity has been distributed uniformly through the thickness of the melt).

Figures 1 and 2 show the maximum thickness of the melt (of the recrystallized layer) as a function of the incident energy density in the case of proton (Fig. 1), ion (B^+, Al^+, P^+, As^+), and laser annealing (Fig. 2). The proton energy is indicated by the numerals at the curves, with the results of ion annealing virtually independent of ion energy (in the range of 60-200 keV). We can see from Fig. 2 that the thickness of the recrystallized layer in the case of laser annealing with a pulse of the same shape and duration is smaller by a factor of more than 3.

The primary limitation on the increase in the thickness of the recrystallized layer through elevation of the density in the declining energy in this model is the surface temperature (it should not reach a level at which intensive vaporization sets in; for Si this is ~2600 K). Figures 2 and 3 show the maximum thickness of the recrystallized Si layer which can be attained by means of proton (Fig. 3), ion, and laser annealing. We see that proton annealing with energies of ~300 keV makes it possible to melt a surface layer with a thickness of less than 3 μm, while with B^+ ions exhibiting energies of 200 keV, the thickness is about 1.2 μm, and in the case of heavier ions or ions with lower energy, the thickness is less than 1 μm; the results from the modeling of laser annealing coincide with those obtained for low-energy ions, i.e., an identical depth of the molten layer (see Fig. 2) corresponds to an idential surface temperature.

It has been demonstrated in [2] that the proposed model well describes the results of proton pulses on silicon in the nanosecond range. Results have been presented in [5] with respect to the B^+ ion beam pulse alloying of silicon at an energy level of 5 keV and a pulse duration of 1 μsec, where the energy density in the beam is 0.5 and 1.5 J/cm^2. According to mass spectroscopy data involving secondary ions at energy densities of 0.5 J/cm^2 virtually all of the boron is localized at the specimen surface, while for 1.5 J/cm^2 the boron ions are distributed through the volume of the substrate to a depth of ~0.52 μm, which can be explained by

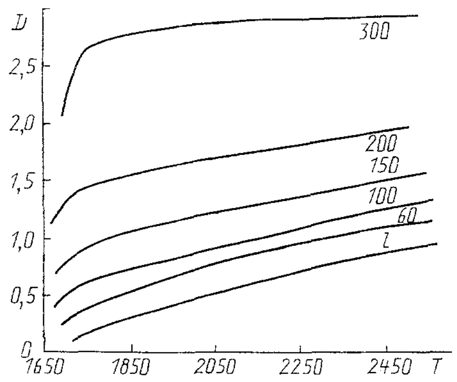

Fig. 3

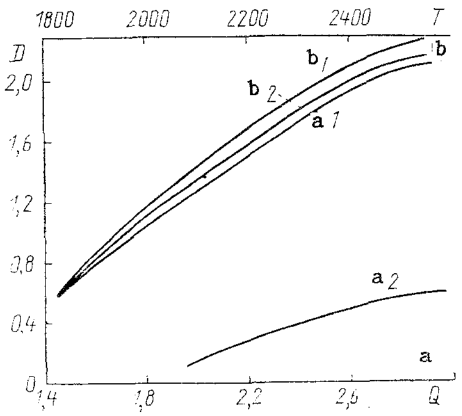

Fig. 4

Fig. 3. Maximum thickness of the recrystallized layer as a function of surface temperature in a proton (60-300 keV) and laser (*l*) pulse of duration 140 nsec.

Fig. 4. Maximum thickness of the recrystallized layer as a function of incident energy density (a) and as a function of surface temperature (b) in a pulse of ions B^+, Al^+, P^+, and As^+ (5 keV) (1) and a laser pulse (2) with a duration of 1 μsec.

the appearance of the melt in the alloying. For purposes of melting the Si surface layer with an ion pulse exhibiting such parameters, according to the estimates in [5], an energy density from 1.8 to 3.0 J/cm^2 is required. It is obvious that the minimum energy is slightly exaggerated: based on the experimental results from [5] melting occurs at an energy density of 1.5 J/cm^2. The results from the model calculations involving pulses of B^+ ions with a duration of 1 μsec and an energy of 5 keV can be seen in Fig. 4. We see that the melting of the Si surface layer occurs at an energy density ranging from ~1.3 to 3 J/cm^2 (at 3 J/cm^2 the surface temperature approaches the boiling point of Si). We can see from Fig. 4 also that when Q = 1.5 J/cm^2 the thickness of the recrystallized layer amounts approximately to 0.6 μm, which is in agreement with the above-cited experimental data.

Comparison with the results obtained in the modeling of laser annealing demonstrates that as in the case of nanosecond pulses, the melt depth at identical energy density is considerably smaller in the case of the laser pulse, while with identical depth the surface temperature is virtually identical (Fig. 4).

Thus, the simple semiconductor heating model examined here, the heating accomplished by an ion pulse beam, can be used to evaluate some of the basic characteristics involved in the process of ion pulse alloying in the self-annealing regime, in the annealing of alloyed layers by ion beams, and to choose optimum regimes for such treatment.

The model calculation results indicate the advantage of the self-annealing ion-alloying regime over those which involve subsequent laser annealing, and especially where the requirement calls for thick or deep alloyed layers.

NOTATION

ρ, density, g/cm^3; c(T), heat capacity, J/(g·K); T, temperature, K; T*, melting point, K; L, latent heat of fusion, J/g; t, time; τ, pulse duration; x, coordinate, cm; K(T), heat conduction, J/(sec·cm·K); E, ion energy, eV; R, reflection factor; Q, density of incident energy, J/cm^2; λ, laser emission wavelength; $\alpha(\lambda)$, laser emission absorption factor.

LITERATURE CITED

1. F. F. Komarov and A. P. Novikov, *Itogi Nauki i Tekhniki, Ser. Fiz. Osnovy Lazernoi i Puchkovoi Tekhnologii*, **5**, 113-161 (1989).
2. Yu. A. Bumai, F. F. Komarov, A. F. Novikov, and A. G. Ul'yashin, *Vestsi Akad. Nauk BSSR, Ser. Fiz.-Mat. Navuk*, No. 3, 92-96 (1987).
3. A. F. Burenkov, F. F. Komarov, M. A. Kumakhov, and M. M. Temkin, *Spatial Distribution of Energy Released in a Cascade of Atomic Collisions with Solids* [in Russian], Moscow (1985).
4. R. Fastow, Y. Maron, and J. Mayer, *Phys. Rev. B.*, **31**, No. 2, 893-898 (1985).
5. J. Piekoszewski, M. Gryzinski, J. Langner, Z. Werner, and G. C. Huth, *J. de Physique*, **43**, 1353 (1982).