Ying C. Kiang
J. Randal Moulic
Wei-Kan Chu
Andrew C. Yen

Modification of Semiconductor Device Characteristics by Lasers

The paper discusses an emerging area of laser-semiconductor processing: the effect of laser irradiation on the electrical parameters of diffused-junction devices. Shallow diffusions of 0.2- to 0.5-μm depths have been achieved. Transistor current gains have been modified and the results agree with the theoretical analysis.

Introduction

Laser processing in the fabrication of integrated circuits has become a rapidly growing and intensely studied field [1] in both academic and industrial laboratories. Interest has centered around the annealing of lattice damage caused by ion implantation, but the precise spatial and temporal control of thermal energy provided by the laser has the potential for use in the formation of extremely shallow junctions and the redistribution of impurities in existing dopant profiles. This paper describes the use of lasers in semiconductor processing for the formation and alteration of impurity profiles. We present an elementary model for laser-induced diffusion using a modified version of Fick's laws, and an experimental verification and correlation of profile characteristics with the input power of the laser. We conclude by showing the redistribution effect of the laser on existing diffused dopant profiles, and by showing how the current gain of a diffused junction transistor can be adjusted.

Motivations for laser-induced diffusion

Emphasis on reducing the geometrical dimensions of integrated devices to improve their speed and power performance has pressed photolithographic resolution to the limits with regard to horizontal dimensions. Micron and submicron dimensions are now the targets for production devices. At the same time, vertical dimensions must be reduced to maintain device depths and more closely controlled dopant profiles. Junction depths of a few tenths of a micron are being discussed. Normal thermal diffusion of such shallow junctions would require one minute or less for a typical dopant source. Clearly, the mechanical problems of raising an entire 100-mm-diameter wafer to diffusion temperatures, maintaining a tolerance of 1°C across the entire surface, and then returning the wafer to ambient temperatures all within one minute is a formidable task. Wide variations in both junction depths and profiles can be expected, resulting in poor tracking of device parameters, even on a single wafer. Ion implantation offers a potential solution, since it allows very precise control of the vertical dimensions of the dopant profile; however, the need to thermally anneal crystal lattice damage caused by the high incident energies of the ions presents a drawback. Precise control in placing the dopant ions can easily be lost by even a short cycle of high-temperature annealing. This problem has been a driving force in the study of laser annealing. The highly localized heating of the silicon by the laser [2] can correct the crystal damage with little movement of the implanted ions. Laser-induced diffusion provides another alternative for the formation of shallow junctions. The pulse width for laser diffusion is usually in the range of 1–200 ns. Thus, the heating and cooling rates of the Si during the laser pulse are $\approx 10^{10}$–10^{12}°C/s. This is sufficient to provide impurity atoms enough time to locate themselves on substitutional sites, but not enough time to diffuse a significant distance from their

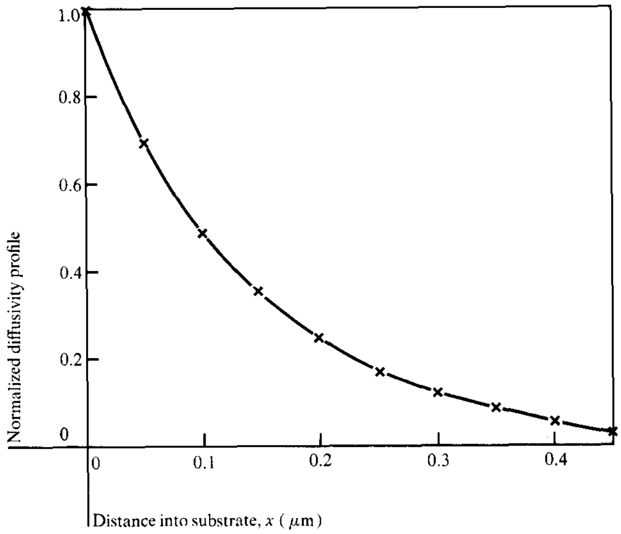

Figure 1 Normalized diffusivity profile as a function of the distance x into the substrate; $D(x) = D(0)\exp(-\alpha x)$.

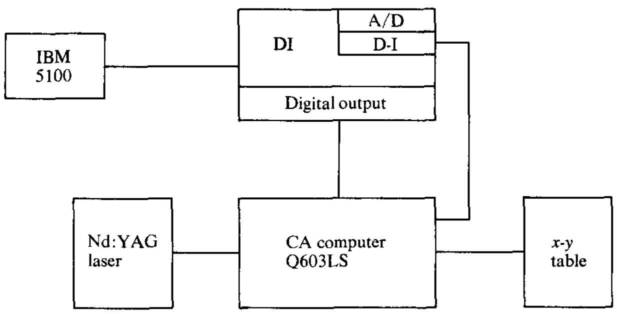

Figure 2 Laser scanning system. The following abbreviations are used: DI = distributed interface, A/D = analog/digital, D-I = digital input, CA = computer-automated, and Q603LS = Quantronix Model 603 Laser Scribe. The Nd-YAG laser is Q-switched and operates at a wavelength of 530 nm.

initial positions. Thus, laser-induced diffusion is expected to provide very sharp diffusion profiles.

Laser-induced diffusion

The localized nature of laser processing allows maskless patterning of diffused areas, a freedom not found in isothermal or ion-implantation systems. The laser can provide a dopant profile wherever it is focused on the surface. High-power optics can provide focused spot sizes of submicron dimensions.

Various researchers have shown that junctions can be formed by applying dopant sources to the wafer and then exposing with a laser. A wide variety of techniques can be used to deposit dopant material on wafers: vacuum evaporation [3], deposition of doped Si [4], and painted coatings [5]. Workers at MIT have used lasers to simultaneously photodecompose a dopant carrying gas directly above the surface of a wafer and, with a second coincident beam, drive the dopant into the surface to form a junction [6]. In our work we selected a commercially available spin-on dopant source. Such films are used throughout the industry in conjunction with normal thermal diffusion processes.

An elementary model of laser-induced diffusion

Solid state diffusion in conventional integrated circuit processing is carried out under isothermal conditions; *i.e.*, the substrate is uniformly heated to a high temperature (900–1300°C) so that the dopant atoms have sufficient energy to move freely through the silicon lattice. The driving force in such diffusion is a gradient in the impurity concentration. Following Fick's laws, the gradient results in a net flow of dopant atoms from regions of high concentration to those of low concentration. Because laser processing is merely localized heating (in all three dimensions), it is appropriate to model its effects with a simple extension of Fick's laws. The modification includes a thermal driving force along the vertical axis (perpendicular to the Si surface), acting in concert with the impurity gradient. Light in the visible spectrum is strongly absorbed in Si [7]; thus, a laser in this range, such as a frequency-doubled Nd:YAG laser (530 nm), is totally absorbed in the top 1–2 μm. At incident intensities of 10–50 MW/cm^2, this gives rise to a thermal gradient with high surface temperatures (>1000°C) and a rapid fall-off to ambient only 5–10 μm below the surface.

We have chosen to incorporate the thermal profile induced by the laser by representing it as a time- and space-dependent diffusivity D. The diffusion coefficient varies rapidly with temperature since there is an exponential dependence:

$$D \propto \exp(-E_a/kT), \qquad (1)$$

where E_a is the activation energy, k is the Boltzmann constant, and T is the absolute temperature. Hence, the proposed diffusivity profile decays even more rapidly than the thermal profile. For example, a 100°C temperature change results in an order-of-magnitude variation in the diffusivity of arsenic in silicon. As a first approximation, we have selected an exponentially decaying diffusivity, based on a similar response of the optical absorption characteristics; see Fig. 1. The decay constant α and the value of the diffusivity at the surface, $D(0)$, must be determined empirically by fitting predictions to measured laser-generated profiles. Incorporating the diffusivity into Fick's first law gives

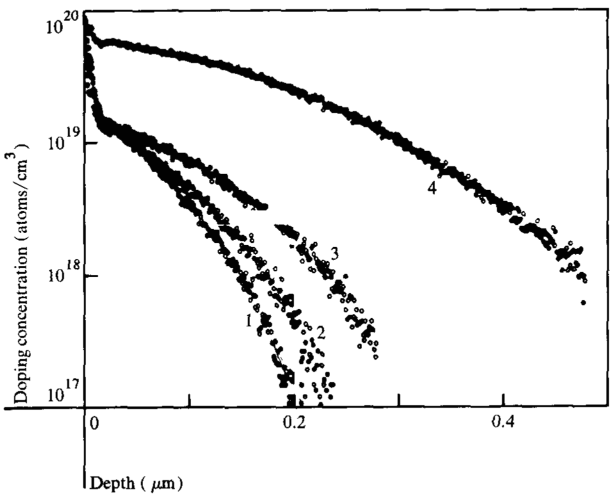

Figure 3 Diffusion profile of the Emulsitone arsenic dopant (EMS3739N); Curves 1–4 represent laser intensities of 19.7, 23.7, 31.2, and 45.2 MW/cm^2.

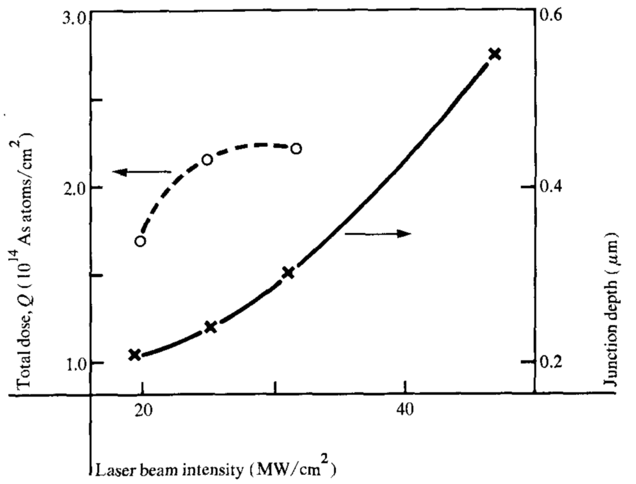

Figure 4 The junction depth (solid curve) and total dose Q (dashed curve) for laser-assisted diffusion as functions of the laser beam intensity.

$$j = -\frac{\partial}{\partial x}[D(x, t)N(x, t)], \tag{2}$$

where j is the dopant flux. Carrying this on to the second law,

$$\frac{\partial N(x, t)}{\partial t} = -\frac{\partial}{\partial x}\left\{\frac{\partial}{\partial x}[D(x, t)N(x, t)]\right\}. \tag{3}$$

Equation (3) was programmed in APL for numerical solution. The results of fitting the prediction to measured results are presented in the next section.

Experimental verification and results

The substrates used for the laser-induced diffusion experiments were ⟨100⟩-oriented, p-type Si wafers. The dopant material for the arsenic diffused layer was a spin-on arsenic source from Emulsitone Co. (Whippany, NJ 07981). Wafers were cleaned in 5% hydrofluoric acid and thoroughly rinsed in deionized water. After N_2 drying, the wafers were immediately coated with solutions of the dopant materials. The resulting film thicknesses were ≈300 nm.

Coated wafers were scanned by a Q-switched frequency-doubled Nd:YAG laser (Quantronix Co., Smithtown, NY 11781, Model 603 laser scribe system). The laser pulse width at half intensity was 135 ns and the repetition rate was 4 kHz; the average power output at 530 nm was 1 W at 4 kHz. Power attenuation is achieved by a set of calibrated neutral density filters. The output beam passed through the corner reflector and beam splitter into a 6.5×, numerical aperture 0.2 objective lens. The beam spot of the objective was elliptical, with a major axis of 25 μm and a minor axis of 20 μm, defined at $1/e^2$ intensity in the focal plane. To enlarge the spot size, we intentionally defocused 990 μm from the focal plane. The resulting spot size at the defocused plane was 53 μm at the major axis and 31 μm at the minor axis. For our applications, we used a computer to control the x-y table motion and the laser firing. The laser scanning system is shown in Fig. 2. A scanning speed of 390 μm/s with a 25-μm step was used, with one shot for each moving step.

Figure 3 shows SIMS measurements of laser-formed dopant profiles. Junction depths ranged from 0.2 to 0.5 μm. Figure 4 shows the junction depth *vs.* laser beam intensity and the total dose of dopant atoms imparted to the Si *vs.* the laser input power.

Fitting of the measured data to the model required trial and error to determine both the surface diffusivity value and the decay constant; see Fig. 5. The surface diffusivities found in cases for laser input powers of 19.7, 23.7, and 31.2 MW/cm^2 were in the range of 0.87×10^{-4} to 1.5×10^{-4} cm^2/s. The surface diffusivity *vs.* laser power intensity is shown in Fig. 6. These values are almost 10^6 times greater than expected in conventional isothermal diffusion, more in keeping with values observed for diffusion in liquids. The incident laser intensity was found to be directly proportional to $D(x, t)$. The decay constant α was determined to be 7×10^4/cm in the three cases. This decay constant is even greater than the optical absorption coefficient for 530-nm light in Si (7×10^3/cm). The last case, for laser input of 45.2

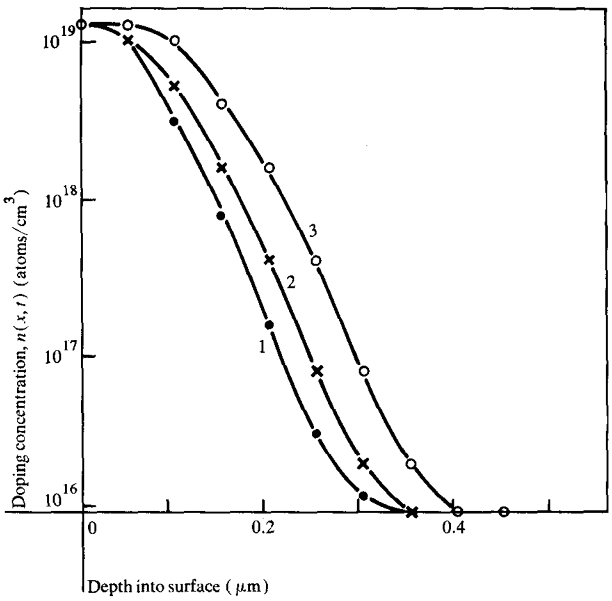

Figure 5 Theoretical diffusion profiles for laser-assisted diffusion in the Emulsitone dopant series. Curves 1–3 correspond to laser intensities given for Curves 1–3 in Fig. 3.

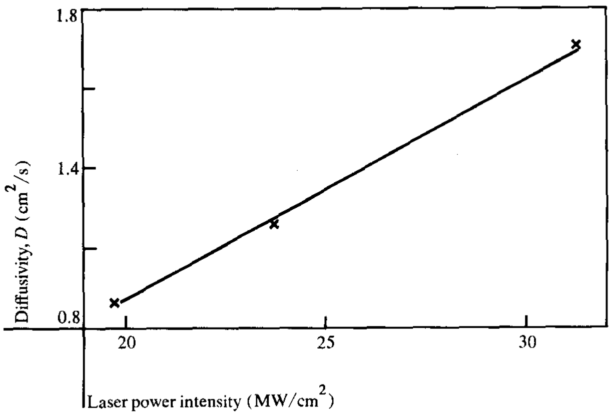

Figure 6 Surface diffusivity D *vs.* laser power intensity.

MW/cm^2, was not fitted to the model because Rutherford backscattering information indicated a high level of damage near the surface for laser intensity >26 MW/cm^2. This is apparently the upper limit for laser-induced diffusion. A scanning electron microscope (SEM) investigation of this sample revealed considerable surface roughness, probably due to splashing of molten material and the removal of some material through evaporation.

Modification of transistor current gain

Transistor current gain β is inversely proportional to the resistivity of the emitter region ρ_E and the base width x_B [8]:

$$\beta \approx \frac{\rho_B L_{NE}}{\rho_E x_B}, \tag{4}$$

where ρ_B is the resistivity of the base region and L_{NE} is the diffusion length of n-type carriers in the emitter region. On the basis of this principle, β can be changed by altering any of the terms ρ_E, x_B, or L_{NE}. To test this concept, data were taken on a series of n-p-n transistors used as process characterization vehicles for a computer logic masterslice technology. The devices have a large emitter area (75 × 275 μm) with a 0.5-μm junction depth. Our laser experiments involved irradiating only the emitter region with a Q-switched frequency-doubled Nd:YAG laser. Transistors without metal contacts were used. Monolithic transistors were obtained just prior to addition of the first level of metal interconnection so that the entire area is overlaid with a blanket layer of quartz, except in the contact regions, which were etched to the bare silicon. Measurements of the current gain were recorded, the transistors were scanned by a laser beam, and measurements were taken again. Hundreds of transistors were evaluated by comparing their dc characteristics. Figure 7 shows the normalized β *vs.* the intensity of the laser beam. It was observed that β decreased considerably. Other researchers have observed similar phenomena and believe some surface damage may have occurred [9]. The samples were then subjected to a low-temperature (600°C) thermal anneal for 10 min under N_2, after which the β were remeasured. Some recovery was noted, though not to the original values; the β were permanently lowered.

To determine whether small changes could be made in the emitter profiles, blanket diffusions were prepared using the spin-on As dopant source and thermal diffusion. SIMS profiles were taken, and then regions of the diffusion were subjected to the same laser conditions as the transistor emitters. SIMS data were taken again and compared to the original. Figure 8 shows the results for shallow (Curves 1 and 2) and deep (Curves 3 and 4) profiles. Note the depression of the surface concentration. Two junction depths of 0.3 and 0.6 μm were used. Laser annealing moved the junction considerably further into the bulk for the shallow diffusion. On the deeper profile, the laser primarily depresses the surface region, altering the bulk region only slightly, as would be expected for actual transistor characteristics.

Using the computer programs for simulating the laser-induced diffusions, we simulated the alternation of existing emitter profiles and resistivities for the range of laser intensities 20–50 MW/cm^2. Combining the predicted resistivity changes (which increased) with Eq. (4), we see that β decreases with increasing laser power. Figure 9 plots the computed β along with the experimentally measured values. In this calculation, we assume that the base width remains fixed, which could be expected on the basis of the 0.5-μm junction depth of the emitter base. We have also assumed that L_{NE} is constant. It is, however, possible that the effect of the laser will alter L_{NE} by changing the carrier lifetime values. The close agreement of our measured and theoretical results leads us to believe that in this case the emitter resistivity change is dominant.

Conclusions

Our experimental results have demonstrated that shallow diffusion profiles of 200 to 300 nm can be obtained using laser diffusion. The rapid and localized heating and cooling of laser processing can also exceed accepted values of dopant solid solubilities, thus allowing the formation of super-doped, shallow junctions. Such junctions could significantly enhance the speed of logic devices.

Laser processing can also be used to redistribute dopant profiles, thereby altering the electrical characteristics of devices. In the case of emitters with diffusion depths greater than 0.5 μm, the current gains of transistors are usually reduced by laser irradiation. However, β can be increased if the emitter has a shallow diffusion profile. The local nature of laser processing permits modification of individual device performance within a wafer, thus providing a trimming capability at the wafer level.

The diffusion profile and β modulation of laser irradiation can be predicted to the first order by a simple modification of conventional diffusion mathematics. These numerical calculations will provide a guide for future experimentation.

Acknowledgments

We appreciate the assistance of R. W. Lang for β measurements, B. J. Ronkese for wafer etching and cleaning, P. Sunders for backscattering measurements, E. F. Gorey for spreading resistance measurements, and B. T. Hwang for thermal diffusions. We also gratefully acknowledge the guidance and stimulating discussions of W. J. Kleinfelder.

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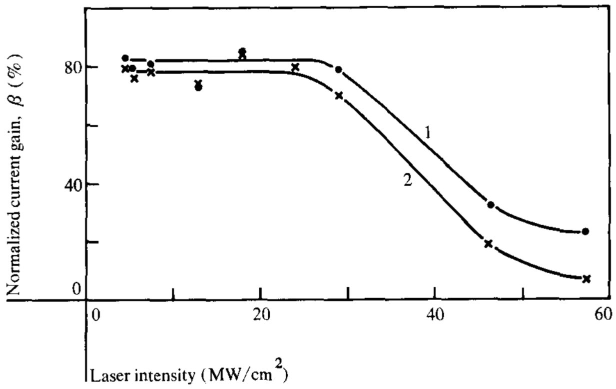

Figure 7 Normalized current gain as a function of the intensity of the scanning laser beam. Curve 1 is for the sample after baking for 10 min at 600°C under N_2. Curve 2 shows the sample after the laser has scanned the emitter region.

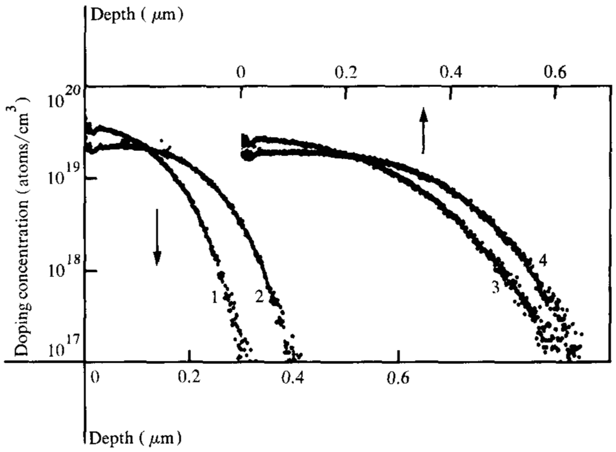

Figure 8 A comparison of thermal diffusion alone (Curves 1 and 3) and thermal diffusion plus laser annealing (Curves 2 and 4) in shallow and deep diffusion profiles.

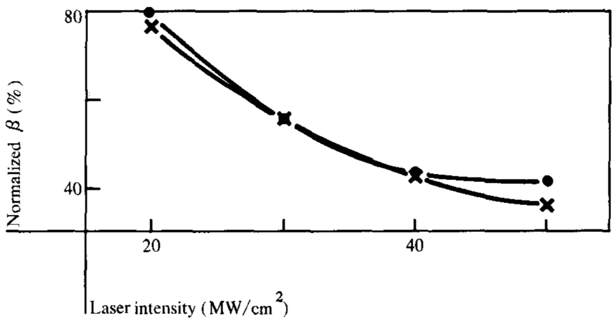

Figure 9 A comparison between the experimental results (●) and the theoretical predictions (×) for the dependence of β on the laser intensity; see Eq. (3).

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Received September 15, 1981; revised October 19, 1981

Ying C. Kiang and J. Randal Moulic are located at the IBM Data Systems Division laboratory, Poughkeepsie, New York 12602. Wei-Kan Chu is currently located at the University of North Carolina, Department of Physics and Astronomy, Chapel Hill, North Carolina 27514. Andrew C. Yen is located at the IBM General Technology Division laboratory, East Fishkill Facility, Hopewell Junction, New York 12533.