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Thermal processing of silicon wafers with microwave co-heating

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Abstract

Microwave heating of differently doped silicon substrates is performed in a 28 GHz applicator installed in a vacuum chamber with gas inlets. In the low temperature regime (<600°C) silicon with low doping levels is faster heated than highly doped silicon. This is explained by the different skin depths of wave penetration. Co-heating by microwave radiation is suggested for low temperature processing with high uniformity and reproducibility. Thermal radiation behaves complementary in the low temperature regime with faster heating of highly doped silicon.

Keywords: Silicon; Thermal processing; Microwave absorption; Skin depth

1. Introduction

Many processing steps in integrated circuit (IC) manufacturing are performed under elevated temperatures, e.g., thermal oxidation, diffusion, implant anneal, chemical vapour deposition (CVD), rapid thermal processing (RTP). Larger wafer diameters and tighter process control impose high requirements on the uniformity and reproducibility of the heating process. These needs direct the attention to some basic limitations of the thermal heating process which are caused by the temperature, doping and surface coverage dependent absorption of radiation. The sum of the reflected portion R, of the absorbed portion A and of the transmitted portion T is unity: $R+A+T=1$. Therefore, changes in the reflectivity caused by both metallic and transparent layers and changes in transmission caused by highly doped regions will change the absorptivity and the related emissivity for radiation. In principle, when heated with the same radiation, processed wafers with different technology or different pattern design will exhibit differences in the mean temperature and they will get local temperature inhomogeneities between regions with different absorptivities. The problems will get worse with the tendency toward lower process temperatures and rapid heating and cooling

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cycles. In temperature transients either absorption or emission dominates, whereas in equilibrium an enhanced absorption is partly cancelled by the enhanced emission. Full cancellation is normally not obtained because of the different spectral ranges of the heater and the substrate radiation, respectively. High temperatures increase the intrinsic carrier concentration of semiconductors by smearing out the transmission differences between different doping levels.

In this paper we will concentrate on low process temperatures and different substrate dopings. We will propose an additional microwave heating and we will give experimental evidence for the complementary nature of the microwave heating.

2. Temperature and doping-dependent infrared absorption

An intrinsic semiconductor at $T=0$ K is completely transparent for photon energies hv (h Planck constant, v frequency of light, λ wave length, c speed of light) below the energy gap E_g of the semiconductor (fundamental absorption). On a wavelength scale this means transparency in the infrared (IR) for wavelengths

$$\lambda \geq hc/E_g = 1.24\ \mu\mathrm{m}/E_g\ (\mathrm{eV}) \tag{1}$$

Blackbody radiation has its maximum intensity in this IR regime as given by Wien's law, e.g., the maximum shrinks from $\lambda=10$ μm to $\lambda=2.5$ μm when the temperature is increased from room temperature to 900°C. The weak absorption and emission in the IR spectral regime causes a fundamental problem with radiation heating of intrinsic semiconductors. Absorption by a completely different mechanism dominates in highly doped or heated semiconductors, namely free carrier absorption. From basic theory [1] the free carrier absorption coefficient α_c follows a dependence on carrier density n and wavelength λ as given by Eq. (2).

$$\alpha_c = K_C n \lambda^2 \tag{2}$$

The constant K_C depends on the scattering dependent intraband relaxation time. Typical values of the constant K_C are 1×10^{-10} and 4×10^{-10} for electrons and holes, respectively, which delivers an absorption coefficient [2,3] of

$$\alpha_c = 25\ \mathrm{cm}^{-1}\ \text{for}\ \lambda = 5\ \mu\mathrm{m}\ \text{and electron concentration}\ n = 1\times10^{18}\ \mathrm{cm}^3$$

As a consequence the IR transparency is reduced considerably ($\alpha_c t > 1$) for sheet carrier concentrations

$$nt > (K_C \lambda^2)^{-1} \tag{3}$$

where t is the thickness of the doped region.

The intrinsic carrier concentration n_i increases strongly with temperature

$$n_i = N_{CV} \exp(-E_g/2kT)$$

(N_{CV} is the effective density of states $\sim T^{3/2}$).

For numerical calculations the bandgap shrinkage [4] should be considered. Following Varshni [5] and Thurmond [6] the bandgap of Si is given as function of temperature T by Eq. (4).

$$E_g\,(\mathrm{eV}) = 1.17 - 4.73 \times 10^{-4} T^2/(T + 636) \tag{4}$$

The intrinsic carrier concentration n_i reaches 8×10^{14} cm^3, 8×10^{16} cm^3 and 1×10^{18} cm^3 for temperatures of 250, 500 and 750°C, respectively, from a low 1.5×10^{10} cm^3 starting point at room temperature. Therefore, at high process temperatures silicon may be considered as opaque independent of the given doping level.

3. Experimental

The dopant and temperature-dependent absorption and emission properties of silicon cause specially at temperatures below 750°C, a more rapid heating and cooling of highly doped substrates or a local temperature difference at highly doped regions.

We propose a heating assistance with a second source of different radiation to compensate for transparency differences. Microwave radiation is suggested as complementary source to thermal radiation. This complementary source should heat low doped regions more rapidly than high doped ones, as shown below.

We applied wave radiation at 28 GHz in six steps of 1 kW each in order to study the microwave heating of doped Si wafers. Samples with specific conductivities from $\sigma_1 = (2\ \Omega\ \mathrm{cm})^{-1} = 50\ (\Omega\mathrm{m})^{-1}$ to $\sigma_2 = (0.02\ \Omega\ \mathrm{cm})^{-1} = 5000\ (\Omega\mathrm{m})^{-1}$ were illuminated in a 28 GHz applicator, a cavity that fulfils the requirements for a diffuse microwave field (multi-mode resonator at $\lambda^3/V \ll 1$). Our 28 GHz applicator [7] consists of a vacuum chamber, a gas inlet for providing low pressure conditions, a substrate holder and the microwave input. Microwave power was generated by a gyrotron operating in pulsed operation at a rep. rate of 50 Hz at a peak power of 15 kW. Power modulation was achieved by variation of pulse width. The 28 GHz microwave radiation, emitted from the gyrotron in a cylindrical TE 02 mode, was transmitted to the applicator via an oversized cylindrical waveguide transmission line consisting of mode conserving bends, filter sections and a mode selective monitor for transmitted and reflected microwave power. The waveguide is feeding the applicator with microwave via a quasi-optical antenna which generates a divergent microwave beam illuminating a moving diffusor plate inside the applicator. By this means the silicon wafers are exposed to a homogeneous diffuse microwave field, a boundary condition which could be proved by diagnostic of microwave intensity distribution with thermography and field scanning with a bolometric probe.

The temperature of the wafers was measured with thermocouples. The result is shown in Fig. 1. It can be seen that the sample with the lower conductivity reaches the higher temperature. This can be understood assuming that the losses are the ohmic losses in the wafers. We show this in the next section.

4. Modelling of the microwave heating

We assume that the loss is mostly due to Ohmic losses, i.e., the currents induced in the wafer by the electromagnetic wave. Then, we have to estimate the skin depth from

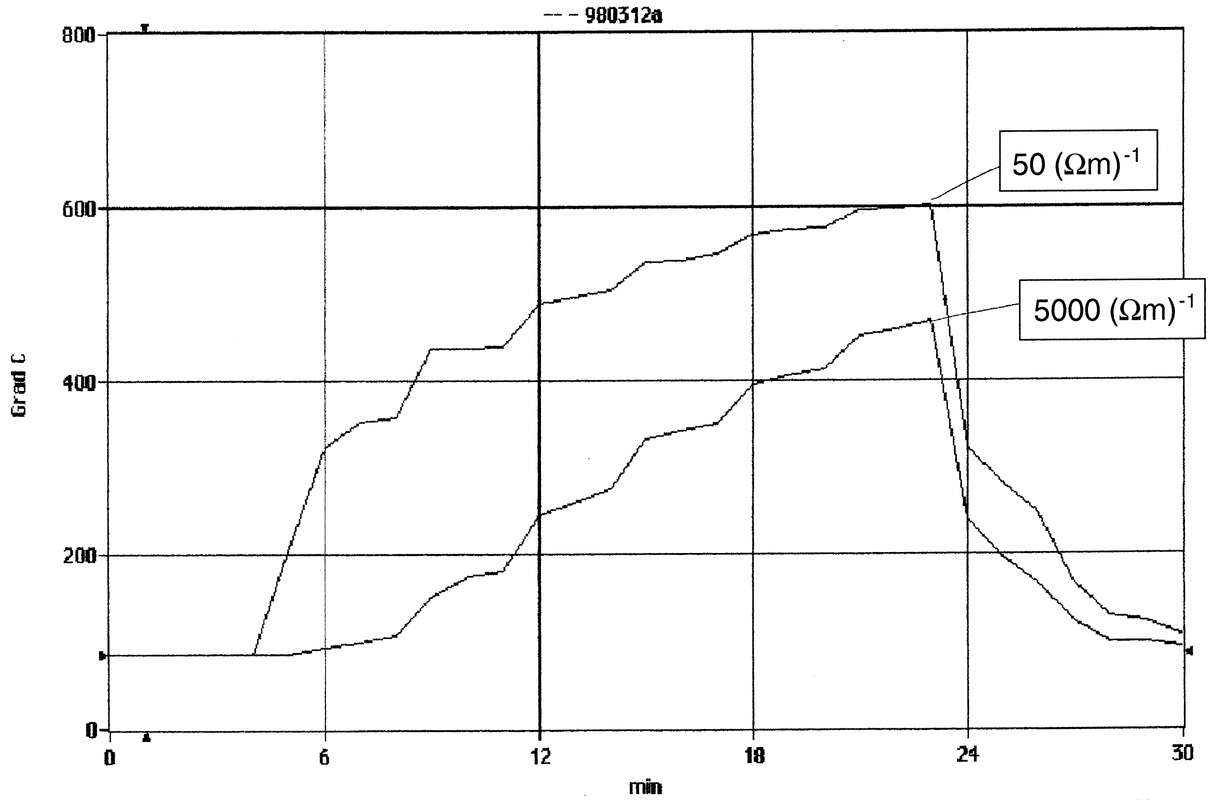

Fig. 1. Experimentally determined temperatures of two Si wafers of different doping when heated with 28 GHz millimetre waves. Power is ramped up in six equidistant steps.

$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}} \tag{5}$$

where σ is the specific electrical conductivity of the material and ω the microwave frequency. For wafer thickness $d \gg \delta$, the wave is fully reflected and for a good conductor (i.e., $\delta \ll \lambda$) the power absorbed on the surface can be calculated by standard electrodynamic theory [8]

$$P_{\mathrm{loss}} = cW_{\mathrm{incident}} 4\pi S\delta/\lambda \tag{6}$$

where S is the surface area of the wafer and $W_{\mathrm{incident}} = 1/2\epsilon_0 E_0^2$ is the energy density of the incoming electromagnetic wave. It can be seen that for $\sigma \rightarrow \infty$, no power is absorbed (ideal reflection). Thus, P will increase when σ is lowered. On the other hand, for $\sigma \rightarrow 0$, the skin depth will exceed the wavelength and the formula above becomes invalid. In this limit, the microwave penetrates the medium without absorption and P will again decrease. It follows that the absorbed power has a maximum somewhere in-between.

Inserting the material constants of the two samples shown in Fig. 1, we obtain:

$\delta_1 = 0.42$ mm for sample 1 with $\sigma_1 = (2\ \Omega\ \text{cm})^{-1} = 50\ (\Omega\text{m})^{-1}$; and
$\delta_2 = 0.042$ mm for sample 2 with $\sigma_2 = (0.02\ \Omega\ \text{cm})^{-1} = 5000\ (\Omega\text{m})^{-1}$

The wafer thickness is $d = 0.52$ mm, so that for sample 1, it is not clear that there is full reflection. Therefore, we have evaluated the reflected and transmitted power fraction as well as the absorbed power for the two cases following [8]. Fig. 2 shows the results as function of the wafer thickness x.

For $\sigma_1 = 50\ (\Omega\ \text{m})^{-1}$, the reflection, transmission and absorption coefficients obtain their bulk values at $x = 3\delta$ and the absorption of 0.43 is close to the maximum achievable value of 0.5. Thus, for small doping, there is efficient coupling to the wafer at 28 GHz. For $\sigma_2 = 5000\ (\Omega\ \text{m})^{-1}$, reflection and transmission already obtain their bulk value at $x/\delta = 1$, i.e., at $0.1d$. Here, the absorbed power has a maximum for $x = 0.025\delta$ and the bulk value of 0.048 is much lower than the maximum of 0.5. In principle, for a given wafer thickness and conductivity one can always find a frequency for which absorption is 0.5, i.e., a matched receiver.

To model the power balance, we assume that the losses are dominated by thermal radiation. This has actually been verified by varying the gas density in the cavity. There was no change in the heating curve, indicating that convection, which should be proportional to the density, does not play a major role. Thus, the following ansatz is made

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \alpha_1 P - \alpha_2 (T^4 - T_0^4) \tag{7}$$

where T is the sample temperature, P the heating power, T_0 the temperature of the surrounding material and the α_i are constants to be fitted or determined from the geometry and the absorption. In our experiment, the power was increased in steps. A result of the modelling of such an experiment is shown in Fig. 3.

One can see that the temporal behaviour is, as in the experiment, dominated by the strong non-linear increase in the radiation losses, leading to a smaller and smaller temperature increase as the power is increased.

In each power step, equilibrium is obtained after some time and the final temperature T_{end} can be calculated according to

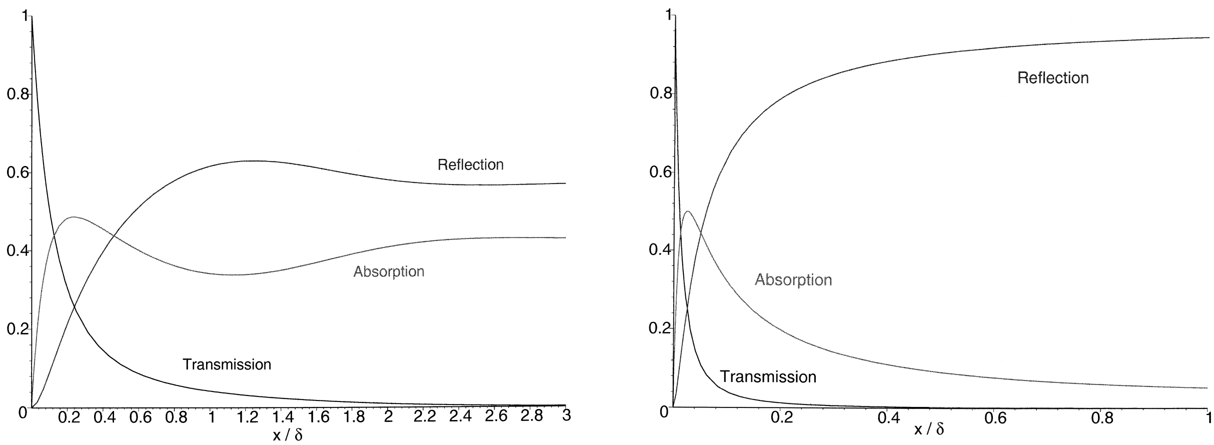

Fig. 2. Reflected, transmitted and absorbed power fraction for $\sigma_1 = 50\ (\Omega\text{m})^{-1}$ (left) and $\sigma_2 = 5000\ (\Omega\text{m})^{-1}$ (right) as function of the wafer thickness x, normalised by the skin depth δ.

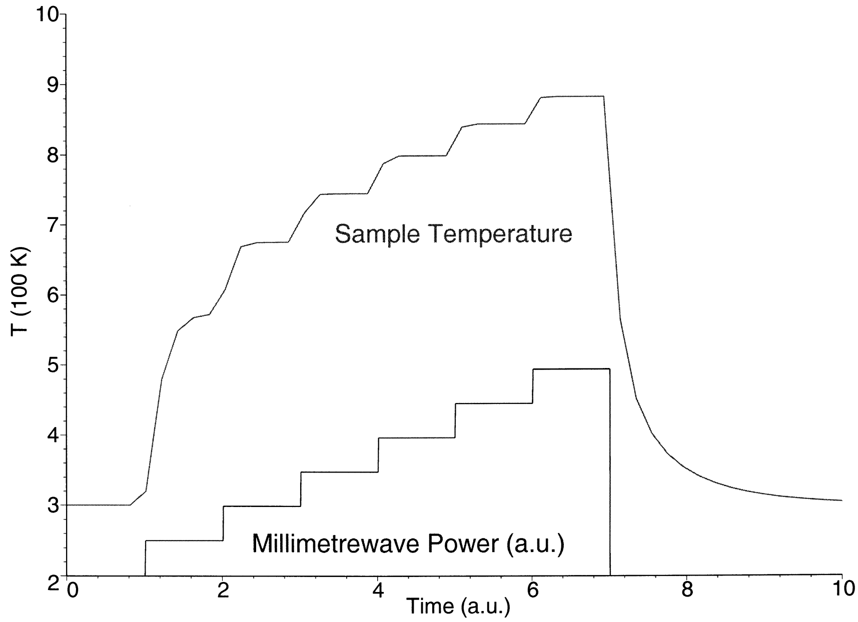

Fig. 3. Modelled heating power and temperature.

$$T_{\mathrm{end}} = \sqrt[4]{\frac{\alpha_1 P + \alpha_2 T_0^4}{\alpha_2}} \tag{8}$$

In the case of ideal reflection, the absorbed power, for equal geometries of the two wafers, only differs by the skin depth, so we expect to see different end temperatures of ratio

$$\frac{T_{\mathrm{end1}}}{T_{\mathrm{end2}}} = \sqrt[4]{\frac{\alpha_3\delta_1 + \alpha_2 T_0^4}{\alpha_3\delta_2 + \alpha_1 T_0^4}} = \sqrt[4]{\frac{\alpha_4 \frac{1}{\sqrt{\sigma_1}} + T_0^4}{\alpha_4 \frac{1}{\sqrt{\sigma_2}} + T_0^4}} \tag{9}$$

where all constants have been put into α_4. At high heating power, we can neglect the T_0 term and thus expect

$$\frac{T_{\mathrm{end1}}}{T_{\mathrm{end2}}} = \sqrt[4]{\frac{\alpha_4 \frac{1}{\sqrt{\sigma_1}}}{\alpha_4 \frac{1}{\sqrt{\sigma_2}}}} = \sqrt[8]{\frac{\sigma_2}{\sigma_1}} \tag{10}$$

For our two samples with $\sigma_2/\sigma_1 \approx 100$, we thus expect a ratio of 1.78. The trend that the probe with smaller conductivity obtains the higher temperature can be seen throughout the experimental ramp up. However, the large factor between the temperatures can only be seen at low heating power (e.g., in the second step, where it is approximately 730 K/450 K = 1.62). This may be attributed to the fact that the conductivities quoted above were measured at room temperature, whereas at $T > 400$°C, the intrinsic conductivity should become important and start to contribute to the total conductivity, so that the ratio between the conductivities will become smaller and actually approach 1 when the intrinsic conductivity dominates.

5. Discussion

The experiments prove that at low temperatures low doped silicon is faster heated by microwave radiation than high doped silicon. The microwave heating is complementary to thermal radiation heating. Assistance of thermal heating by microwave power may therefore reduce reproducibility problems with different substrate types and local heating of high doped regions. The heating is doping-dependent only in the temperature regime below 750°C when the intrinsic carrier concentration is low enough to allow for a partial IR transparency of low doped silicon regions. Future processing with low temperature budgets will be influenced more by this effect. The temperature budgets will be reduced to get sharper doping transitions in mainstream technology and to allow the insertion of silicon-based heterostructures. In the area of high frequency bipolar transistor the SiGe heterobipolar transistor (SiGe–HBT) is rapidly replacing the silicon only bipolar junction (BJT) [9] with stringent needs for process temperatures below 900°C. Future hetero CMOS and optoelectronic devices based on SiGe/Si [10] require even stricter temperature limits. Furthermore, the microwave power assistance may reduce the thermal power needs with beneficial effects on the vacuum conditions.

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References

[1] P.Y. Yu, M. Cardona, in: Fundamentals of Semiconductors, Springer, Berlin, 1995.
[2] A.R. Hilton, C.E. Jones, J. Electrochem. Soc. 113 (1966) 472.
[3] H.Y. Fan, M. Becker, Phys. Rev. 92 (1950) 178.
[4] Properties of Silicon, Emis Data Reviews Series 4, INSPEC, London, 1988.
[5] Y.P. Varshni, Phys. A 34 (1967) 149.
[6] C.D. Thurmond, The standard thermodynamic function of the formation of electrons and holes in Ge, Si, GaAs, GaP, J. Electrochem. Soc. 122 (1975) 1133–1141.
[7] G. Muller, P. Mehringer, New developments in technology for millimetre-wave processing of materials, in: Proc. Int. Symp. on Microwave, Plasma and Thermomechanical Processing of Advanced Materials, JWRI, Osaka, 1997.
[8] M. Born, E. Wolf, in: Principles of Optics, 5th Edition, Pergamon, New York, 1975, p. 624.
[9] E. Kasper, J. Eberhardt, Physics of future ultrahigh speed transistors, in: 29th European Microwave Conference Proceedings, Vol. 1, 1999, p. 151.
[10] S. Luryi, J. Xu, A. Zaslavsky (Eds.), Future Trends in Microelectronics, Wiley, New York, 1999.