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Determination of the thermal cycle during flash lamp annealing without a direct temperature measurement

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ABSTRACT

Flash lamp annealing (FLA) is a modern annealing technique which, starting from microelectronics, has spread over new application areas like flexible electronics, photovoltaics or thin film deposition. Because of the short annealing time in the range of milliseconds and below, FLA allows the suppression of unwanted processes like diffusion, the annealing of temperature-sensible substrates, and the saving of process time and energy. In addition, it is predestined for roll-to-roll applications. However, the determination of the thermal cycle during FLA is challenging. The existing methods for a direct temperature measurement, mostly based on pyrometry, are elaborate and have to solve the problem to detect thermal radiation against the background of the intense flash light. An alternative way is simulation, but now an extended knowledge about the flash and the material system to be flashed is needed. In this work we describe a methodology to determine the thermal cycle during FLA without the need for a direct temperature measurement. This methodology is based on an optical-thermodynamic simulation *and* calibration experiments which can be implemented with reasonable effort under certain assumptions. The simulation considers not only the properties of the flash and the sample, but also the reflectivity of the chamber walls. Finally, the pros and cons of this methodology are shortly discussed.

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1. Introduction

Flash lamp annealing (FLA), sometimes also called intense pulsed light or photonic sintering, is a modern annealing technique which had been gradually introduced in microelectronics industry at the turn of the millennium, but has quickly moved into new areas of application such as flexible electronics [1], photovoltaics [2] or thin film deposition like flash lamp assisted atomic layer deposition [3]. FLA with annealing times in the ms and sub-ms range operates in thermodynamic non-equilibrium which allows the annealing of surface-close regions and to selectively suppress unwanted processes like dopant diffusion. In addition, the backside will face, depending on the pulse length of the flash and the specific material system, a significantly lower temperature than the surface. Due to the short time scale of annealing FLA is also predestined for roll-to-roll applications. More details about the technology and potential applications of FLA can be found in [4–6].

However, the short time scale comes with its own challenges. Thermal stress may lead to wafer bowing [7], warpage of glass carriers [8,9] or delamination of thin layers [10]. Another problem is temperature measurement, or more precisely, the determination and quantitative description of the thermal cycle a surface and surface-close region undergoes during FLA. The difficulties are that temperature changes within ms or faster, that these changes strongly vary with depth, and that they additional depend on the optical and thermodynamic properties of the sample. Most approaches use optical, contactless methods like the thermawave technique [11], polaradiometry [12] or pyrometry to measure the temperature during FLA. Pyrometry is the most common method, but all of them require an a priori knowledge about the optical properties of the sample, first of all reflectivity or emissivity, and the measurement signal is usually outshined by the high intensity of the flash light. To solve the latter problem, the diagnostic wavelength of a pyrometric measurement can be blocked in the flash lamp spectrum, e.g. by using water [13] or a hydroxylated synthetic quartz glass window [14,15]. There is a sophisticated but elaborate method called Flat-Top Flash Annealing™ [16,17] in which the temperature measurement feeds a feedback loop to control the flash lamp current in real time. An overview about the different methods to measure temperature during FLA can also be found in [15].

An alternative way is to simulate temperature. This avoids the addressed technical problems of a temperature measurement,

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but now an extended knowledge about the flash and the material system to be flashed is needed. In this work we describe a methodology to determine the thermal cycle during FLA without the need for a direct temperature measurement during the flash. This methodology considers not only the properties of the flash and the sample, but also the reflectivity of the chamber walls. To do so, the work is divided into three parts. The first one reports on surface melting experiments performed in different chamber configurations with different reflections. Based on this, a model is introduced which considers the effect of different chamber configurations in order to estimate the true fraction of flash light which is really absorbed in a sample. The third part describes how the temperature profile in time and space can be obtained by an optical-thermodynamic simulation with reasonable effort. Finally, the pros and cons of this methodology are shortly discussed.

2. Experimental

FLA was performed on a non-commercial 100 mm tool which consists of four flash lamp circuitries, whereby each circuitry has three flash lamps with an arc length of 25 cm and being connected in series. The flash lamps are arranged in two planes which have a slight offset relative to each other in order to homogeneously irradiate the area of a 100 mm wafer. The geometry of the chamber made of Al is sketched in Fig. 1. The pulse forming network comprises a capacitance of 6 mF and a coil of 5 mH which results in a pulse length of about 12 ms. FLA was performed under atmospheric pressure in a nitrogen ambient. Preheating of 150 s was carried out by halogen lamps from the backside. The flash pulse is characterized by a pulse shape, its spectrum and its intensity, whereas the latter is usually measured in terms of energy density on a sample surface. Furthermore, the measurement of the corresponding current and voltage profile can give additional information. In this work light, current and voltage pulses were simultaneously recorded with a four-channel Rigol DS1000Z digital oscilloscope in combination with a Thorlabs FDS100 photodiode, a Rogowski coil CWT30B, and a 1:1000 voltage divider, respectively. The time-averaged spectrum was measured with an Avantes AvaSpec-2048 spectrometer and an accumulation time of 20 ms. In order to guard the photodiode and the spectrometer from the high intensity of the flash, the light was attenuated with a set of neutral density filters with known transmission whose combined optical density was between 4 and 5. The energy density was estimated by an Integra UP19-15S power detector in energy mode.

Three types of samples with a size of $10 \times 10\ \text{mm}^2$ were used for the calibration experiments. Si and Ge samples were cut out from a 100 mm (1 0 0)-oriented Si or Ge wafer as well as a 50 mm (1 0 0)-oriented Si wafer. The thicknesses of these samples are 525 μm (Si), 275 μm (Si) and 175 μm (Ge). To check the influence of chamber wall reflections, the samples were flashed in three different configurations: lying on a 100 mm Si wafer (thickness 525 μm), lying on a *quarter* of a 100 mm Si wafer (thickness 525 μm), and lying on a 100 mm quartz glass plate. In the following, these configurations which mainly differ in reflectance are denoted as Si full wafer, Si quarter wafer and quartz configuration. Thus, depending on configuration the term substrate denotes a full Si wafer, a quarter Si wafer or a quartz plate. The first occurrence of melt seeds is determined by an optical Zeiss AxioScope microscope.

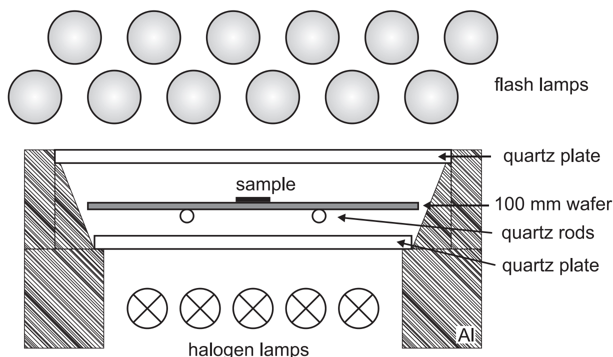

Fig. 1. Basic scheme of the chamber geometry. Different chamber configurations differ by the type of the substrate.

Optical simulations of the absorption profile and the reflectance of the samples are performed by the wave transfer matrix method [18]. Both are obtained by a weighted average over the flash lamp spectrum on the energy scale. Optical constants for Si and Ge were taken from [19]. The optical simulation can be avoided by measuring the reflectance directly and approximating the absorption by an equivalent heat source at the surface. In case of bulk Si annealed by FLA it was found that the difference between an explicit absorption profile and a surface heat source is in the order of 10 K and less [20]. In the present case the absorption profile was considered, and one-dimensional temperature profiles $T(x,t)$ were calculated by using the COMSOL Multiphysics© software. Thereby, the temperature dependence of heat capacity and heat conduction of Si and Ge was considered by using corresponding literature data [21,22]. Heat dissipation by thermal radiation and heat convection was considered by using a constant emissivity and a heat transfer coefficient of 1-R_S and 20 W m^{-2} K^{-1}, respectively. However, these processes were found to be insignificant on the ms time scale. In this approach the optical simulation is decoupled from the thermodynamic simulation which allows the calculation of reflectance and of the absorption profile in advance of the thermodynamic simulation.

3. Results and discussion

3.1. The surface melting experiment

The samples were annealed in each configuration by FLA with 12 ms pulses and increasing energy density in order to find the threshold where first melt seeds will occur *in the middle* of the samples. It has to be considered that first melt seeds will already occur at lower energy densities at the corners and the edges. This is due to the additional absorption of light at the side faces leading to an additional heating there [4,23]. Fig. 2 shows the first appearance of melt traces in the middle of the samples for the Si quarter wafer configuration.

The threshold to achieve surface melting is given in Table 1 in terms of preheating temperature and measured energy density E_D. The table reveals two clear tendencies: for a given configuration, the thermal budget increases in the order Ge 175 μm, Si 275 μm and Si 525 μm, and for a given sample the thermal budget increases in the order of Si full wafer, Si quarter wafer and quartz configuration. The difference between Ge and Si is simply due to the different melting points of 938 °C and 1410 °C, respectively. The lower value for the thinner Si sample is due to the smaller heat conduction towards the backside. However, the second tendency was not expected in such a significant manner. Intuitively, one would expect a flash light fraction of $(1 - R_S)$ being absorbed by an opaque sample where R_S is the reflectance of the sample. In such a case the threshold value in Table 1 should not depend on the configuration. In fact, the reflectance of a Si wafer is much higher than that of a quartz plate indicating that back reflection from the substrate followed by a second reflection in the upper half of the chamber has a significant impact. Thus, in case of the Si full wafer

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