INFRARED HEATING WITH OPAQUE QUARTZ REFLECTOR TECHNOLOGY

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ABSTRACT

To ensure the performance of the OTB Solar deposition tools, we utilize a novel opaque quartz reflector technology for our short-wave infrared lamps. The opaque quartz reflector has a superior industrial robustness over conventional reflector technologies.

Angular intensity measurements show that the reflectance of the opaque quartz material can compete with that of a gold reflector. In the near future, further developed opaque quartz reflectors with a reflectance close to that of gold are foreseen.

SOLAR INDUSTRY AND INFRARED HEATING

The high throughput demands on production machines in solar industry impose developments towards short wafer process times in order to limit footprint. Short process times in thermal production steps are achieved by using short-wave infrared lamps, exploiting the direct radiation absorption of crystalline silicon below wavelengths of 1.1 µm [1]. One example of the application of short-wave infrared lamp heaters is the conveyor furnace used for firing of metallization pastes. Due to the combination of short-wave infrared radiation and considerable conveyor speeds, extremely fast temperature ramp-ups can be achieved. Another advantage of this type of heater is the relative ease of coupling the radiation efficiently into vacuum through dedicated quartz tubes. This approach is applied in the deposition tools of OTB Solar.

OTB SOLAR DEPx DEPOSITION TOOL

Our deposition tools (DEPx) are developed for the high-throughput processing of a silicon nitride anti-reflection coating. Deposition is performed by means of remote plasma enhanced chemical vapor deposition involving silane and ammonia precursor gasses [2,3]. Wafers are transported in vacuum by carriers that pass through the process chamber. A view of the process chamber is shown in Fig. 1. To couple the radiant energy into the vacuum, the lamp heaters are mounted inside quartz tubes. The quartz tube design ensures fast lamp replacement without the necessity of breaking the vacuum. The lamps are short-

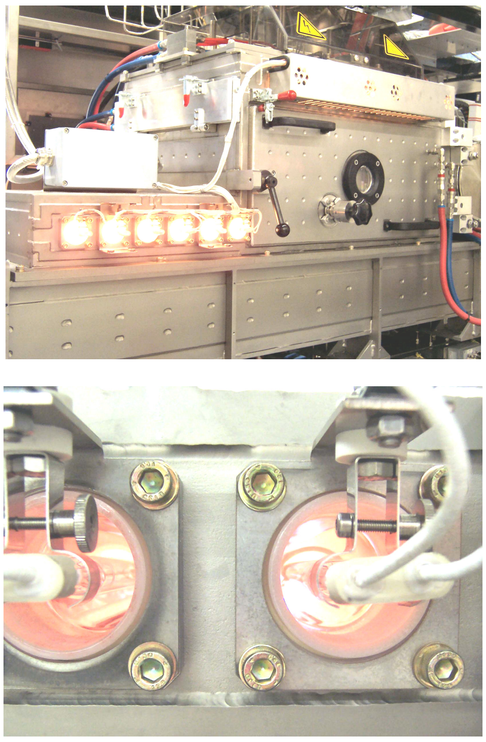

Fig. 1. The DEPx process chamber (top) with detailed view of lamps inside the quartz tubes through which the radiation energy is fed into the vacuum (bottom).

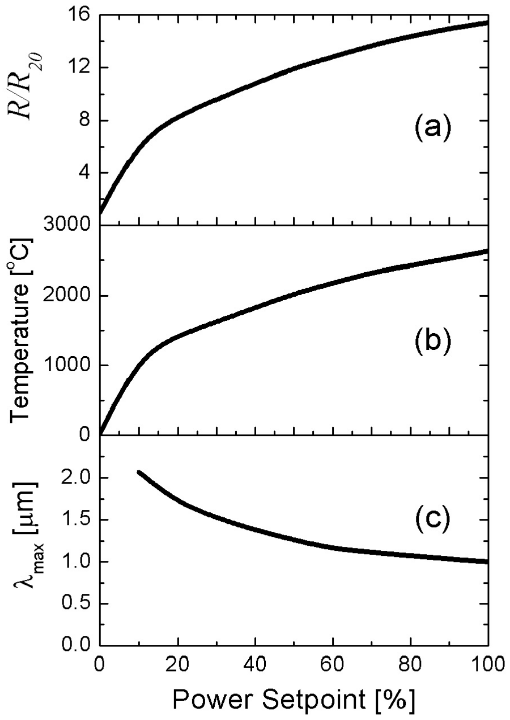

Fig. 2. Filament resistance (a), calculated filament temperature (b), and corresponding maximum spectrum position (c) as a function of the DEPx tool lamp power setpoint.

wave infrared twin-tube emitters with tungsten filaments manufactured by Heraeus Noblelight.

Before the reflector technology is discussed, we briefly mention here the dependence of the radiant spectrum on the power setpoint of the DEPx tool. Fig. 2-(a) shows the resistance of the tungsten filament normalized to its value at 20 ^{o}C. The corresponding filament temperature shown in Fig. 2-(b) is calculated from the temperature dependence of R/R_{20} known for tungsten [4]. The position in wavelength of the energy spectrum maximum according to Wien's law [5] is shown in Fig.2-(c). This result indicates that already above 60 % power setpoint, the energy spectrum maximum is close to the 1.1 µm absorption edge of silicon.

REFLECTOR TECHNOLOGY

The lamps are equipped with reflectors to enhance the heating efficiency and to keep the temperature of surrounding chamber walls relatively cool. During operation conditions, the air temperature inside the quartz tube can exceed 1000 ^{o}C. This imposes stringent thermal stability requirements on the reflector material.

Basically two types of reflectors exist: Metallic and non-metallic. Metallic reflectors are specular and, as a consequence, the shape of the reflector can be designed to focus the radiant energy. Non-metallic reflectors are generally diffuse, i.e. each point of the reflector surface acts as an isotropic point source of radiation. Therefore, in contrast to the specular metallic reflectors, it is not possible to realize a focus. An advantage of diffuse reflection, however, is the ability to reach improved temperature uniformity.

One example of a non-metallic reflector is alumina. This ceramic can offer a reasonable reflectance and is frequently applied in laser systems. Exposed to air at 1000 ^{o}C, however, the reflectance of alumina is known to degrade as a result of chemical reduction with carbon. This makes alumina less suited for our application.

GOLD VS. OPAQUE QUARTZ

Here we address the applicability of gold and opaque quartz as reflector material. Gold is a reflector with an excellent chemical stability and reflectance exceeding 95 % over a broad wavelength range. Fig. 3-(a) shows a twin-tube lamp equipped with a gold reflection coating. The angular Intensity distribution obtained with this reflector is shown in Fig. 4-(a). By considering the ratio between forward (0^{o}) and backward (180^{o}) intensity in a simple one-dimensional model, one can deduce that the reflectance R is about 95 %. In our application, however, we have found that the high ambient temperatures cause the gold coating to evaporate from the quartz surface of the lamp. Typically this leads to a degradation of the reflectance from its initial value to below 75 % in a period as short as several days. By applying a special high-temperature gold coating, this degradation period could be extended to several weeks. In a continuous production environment, such degradation is not only limiting the useful lifetime of the lamp, but, more importantly, causes an unaffordable process drift of the silicon nitride deposition.

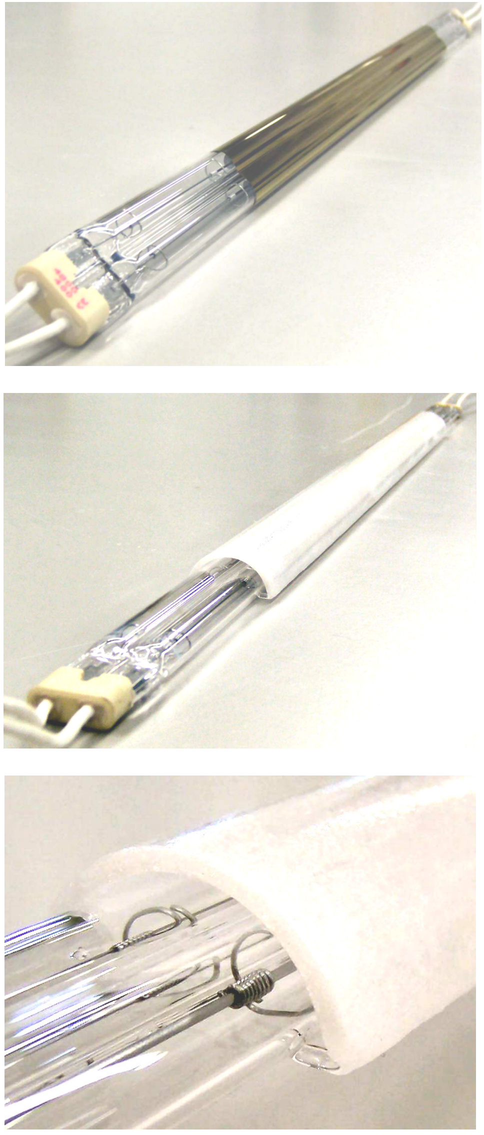

Fig. 3. Twin-tube lamp with gold coating (a) and welded semi-circle opaque quartz reflector (b and c).

As stable process conditions are essential, thermal robustness of the reflector material is more valuable than a high magnitude of the reflectance. Absolute thermal robustness is achieved by utilizing opaque quartz reflector materials. Fig. 3-(b and c) show a semi-circle shaped reflector that is welded onto the lamp. The angular intensity distribution obtained with this opaque quartz is shown in Fig. 4-(b). From the distribution a reflectance of about 40 %

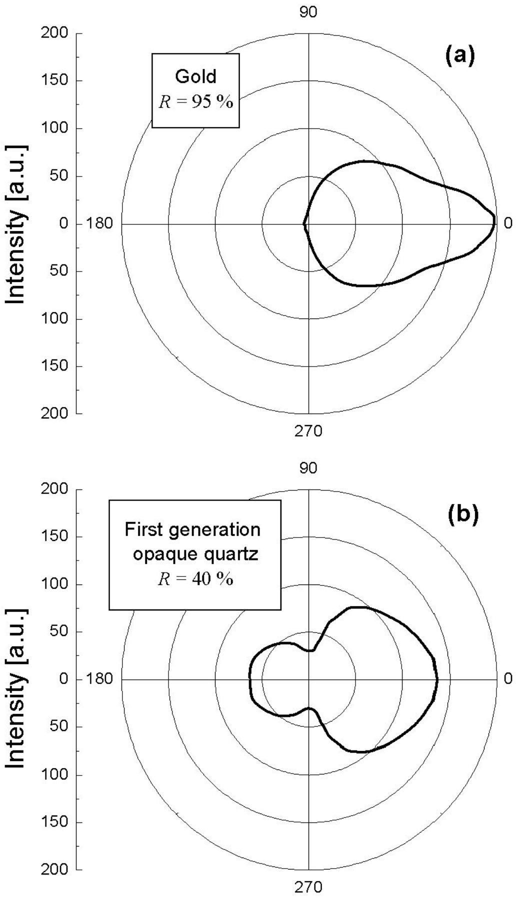

Fig. 4. Angular intensity of the emitter with gold reflector (a) and the first generation opaque quartz reflector (b).

can be deduced. The wafer temperature and heat shielding in our application is competing with that obtained with gold reflectors. Currently, opaque quartz reflector technology is under development by Heraeus Noblelight and a significantly enhanced reflectance is foreseen. The fact that a high reflectance can be obtained can be understood by considering the microscopic structure of opaque quartz.

OPAQUE QUARTZ AND DIFFUSE REFLECTION

Opaque quartz has its white appearance due to the scattering of light at micrometer-sized bubbles. Although the scattering at each bubble is arbitrary, in principle all incoming light can be reflected. This can be quantified by considering a simple one-dimensional series of arbitrary scattering centers. When t is the length of the series and a the distance between each scattering center, then the total reflection R is given by

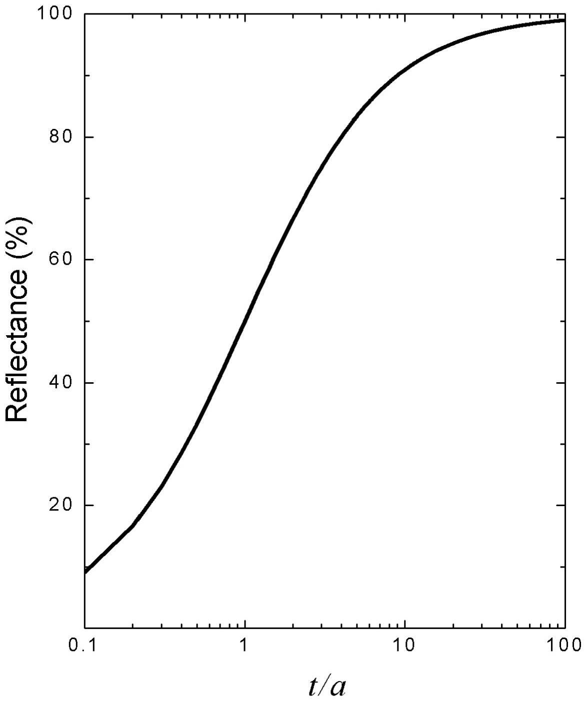

Fig. 5. Reflectance of an absorption-free one-dimensional diffuse reflector.

$$R = \frac{1}{1 + a/t}. \qquad (1)$$

This equation is a good approximation for the reflection of opaque quartz with negligible absorption. In this approximation t can be regarded as the thickness and a as the scattering mean free path. The mean free path is determined by the bubble density and bubble diameter. The dependence of R on the normalized reflector thickness t/a is shown in Fig. 5. When the thickness is much larger than the scattering mean free path, the reflectance approaches 100 %. The opaque quartz reflector technology currently under development is based on a material with a smaller scattering mean free path.

SUMMARY

The short-wave infrared lamps of the OTB DEPx tools are equipped with reflectors for heat shielding and to enhance heating efficiency. The necessity of stable deposition conditions and the high–temperature reflector environment impose stringent requirement on the reflector material. Stability obtained with conventional gold reflector coatings is not sufficient due to the evaporation of the gold coating over time. Lamps equipped with opaque quartz reflectors offer absolute thermal stability and a considerable reflectance. The reflectance of opaque quartz is enhanced by reducing its optical mean scattering length.

ACKNOWLEDGEMENT

The authors thank J. Eckert and A. Schwarzmann of Heraeus Noblelight for useful suggestions and providing the angular intensity data.

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