**Letter**

**Measurement of Vacuum Ultraviolet Radiation of Low-Pressure Mercury Lamps Using Photoconductors Made of Synthetic Diamond Films**

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**ABSTRACT**

A new type of robust photoconductor made of synthetic diamond films was evaluated for measurement of vacuum ultraviolet (VUV) radiation irradiated by low-pressure mercury lamps. It was demonstrated that the diamond sensors are suited to directly measure intensity of 185 nm line among various radiations from low-pressure mercury lamps. Decrease in contact angles of water droplets on UV-treated glass substrates was more closely correlated with the irradiance of 185 nm as compared to that of 254 nm from low-pressure mercury lamps, indicating importance of direct monitoring of the former. The diamond sensors were very stable and did not degrade for 100 hours under the 185 nm irradiation of about 2 mW/cm², showing potential usefulness of the sensors for monitoring and controlling of various VUV processes.

**KEYWORDS:** diamond films, photoconductor, low-pressure mercury lamp, measurement of 185 nm irradiation

1. Introduction

Intense vacuum ultraviolet (VUV) radiation sources such as xenon (Xe) excimer lamps (λ = 172 nm) and low-pressure mercury (Hg) lamps (λ = 185 nm) are increasingly used for various processes in fabricating semiconductor devices and flat panel displays. Though it is ideal to monitor the irradiance of the VUV radiation sources all the time during such processing, there has been no tool to realize the continuous monitoring. Existing sensors such as silicon photodiodes are seriously degraded under long-term exposure to intense VUV radiation.

Diamond is a material that possesses excellent chemical inertness and durability to high energy radiations. Because its band-gap energy (5.5 eV) corresponds to the wavelength of 227 nm, diamond absorbs only VUV radiations. It has thus been considered a potentially suitable material for solar-insensitive VUV detectors which are stable under intense VUV radiations³. We have previously evaluated the diamond sensors to measure VUV radiations from ArF excimer lasers and Xe excimer lamps²⁰²³. In this study, VUV radiations from low-pressure mercury lamps were measured using the photoconductors.

2. Low-pressure mercury lamps

Low-pressure mercury lamps radiate at various wavelength (185, 254, 365, 405, and 546 nm) as shown in Figure 1. Among the irradiations, it has been believed that the 185 and 254 nm irradiations play important roles for the VUV processes. However, their detailed mechanism has not been revealed yet partially because there has not been a reliable sensor to directly measure the 185 nm irradiation. Irradiance from low-pressure mercury lamps has been conventionally measured by rotating a filter wheel in front of a photodiode.

![Figure 1](image-url) A typical spectrum of VUV radiation from low-pressure mercury lamps
determined by measuring the 254 nm irradiance. The 185 nm irradiance was calculated from the 254 nm irradiance. It has been generally believed that the 185 nm irradiance is about 10 - 30% of the 254 nm irradiance.

3. Diamond sensors

The photocductive sensors used in this study were fabricated by placing a pair of interdigitated platinum micro-electrodes on the surface of insulating synthetic diamond films where current is generated by photon irradiation with energy greater than its optical bandgap. The device, with the sensing area of 2.0×2.0 mm², was enclosed in a standard hermetic seal (TO-5 package) in an inert gas atmosphere with a sapphire window of high UV-transmittance down to 140 nm⁶. Packaged diamond sensors are shown in Figure 2.

Figure 3 shows a typical responsivity of the packaged sensors.⁷ The spectrum was obtained using a monochromated radiation from a deuterium lamp in the wavelength range between 120 nm and 250 nm. The sensor has maximum sensitivity around 190 nm and a cut-off at 227 nm that corresponds to the bandgap energy of diamond.

4. Results

4.1 Direct measurement of the 185 nm irradiation

The results shown in Figure 4 indicate that the diamond sensor detects only the 185 nm irradiation from the low-pressure mercury lamp. The radiation was measured with two kinds of windows placed between the lamp and a sensor. One of them (Window B) transmits the 185 nm irradiation while the other (Window A) blocks it off as plotted in Figure 4 (a). The sensor signal was completely turned off with Window A, while the signal was detected with Window B as shown in Figure 4 (b). It was confirmed that the diamond sensor was insensitive except for the 185 nm irradiation such as 254 nm from the low-pressure mercury lamp.

4.2 Stability of the diamond sensors

Figure 5 shows the long-term stability of the diamond sensors for a continuous irradiation of a low-pressure mercury lamp (GWH1101F-3, Iwasaki Electric). The 185 nm irradiance was approximately 2 mW/cm².

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![Figure 2 - Packaged diamond sensors](image)

![Figure 3 - A typical responsivity of the packaged diamond sensor](image)

![Figure 4 (a) - Transmittance of two kinds of glass plates used in the experiment](image)

![Figure 4 (b) - Output photocurrent of a diamond sensor when the two kinds of glass plates placed between the low-pressure mercury lamp and the sensor](image)

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The output signal of the diamond sensor was measured every 5 hours, while the sensor was exposed to radiation from the lamp throughout the test. The signal was stable within ±3 % for 100 hours.

4.3 The 185- and 254-nm irradiances from low-pressure mercury lamps

Figure 6 shows the 185 nm irradiance measured using a diamond sensor for a low-pressure mercury lamp (QCL600U-3, Iwasaki Electric) at various temperatures of cooling water for its bulb. It was observed that the 185 nm irradiation is optimum at the water temperature of 50 °C for this lamp.

It is empirically known that there is an optimum vapor pressure of mercury in low-pressure mercury lamps to radiate UV lines of higher energy (185 and 254 nm). When the mercury pressure exceeds the optimum range at elevated temperatures, the resonance radiation is imprisoned and the radiations in the visible and low-energy UV increase. It is considered that in this lamp mercury atoms and electrons is balanced at the water temperature of 50 °C.

For the same lamp, the 254 nm irradiance was measured at various cooling water temperature using a UV irradiance meter (UVPF-A1, Iwasaki Electric). It was found that the 254 nm irradiance shows different temperature dependence for 185 nm irradiance and peaked at 40 °C as shown in Figure 7, thus indicated the value of the direct measurement of the 185 nm irradiance.

4.4 The relationship between contact angles and 185 nm accumulated irradiance

Surface cleaning of glass substrates was conducted using two different low-pressure mercury lamps whose luminescent tube are made of different materials (lamp a: synthetic quartz glass that is transparent for 185 nm, and lamp b: doped silica glass in which the radiation is partially absorbed). The accumulated irradiance of the 185 nm radiation was measured by a diamond sensor while that for the 254 nm radiation was measured with the NIST-traceable Si photodiode. Figure 8 shows the relationship between the contact angles of water droplets, reflecting surface contaminants on the glass substrates, and the accumulated irradiances of the 185 and 254 nm radiations.

It was observed that the contact angle decreased as the accumulated irradiances increased. The contact angle was well-correlated with the accumulated irradiance of the 185 nm radiation as shown in Figure 8 (a). On the other hand, an apparent split was observed for the accumulated irradiance from the 254 nm radiation, especially in the range between 400 and 2000 mJ/cm². The direct measurement of 185 nm radiation was thus found important in the dry cleaning process of the glass substrate.
5 Conclusions

Measurement of the VUV radiation from the low-pressure mercury lamps were conducted using diamond sensors. It was confirmed that the diamond sensors are sensitive only to the 185 nm radiation among various irradiation from low-pressure mercury lamps. The contact angles of water droplets on glass substrates, which represent concentration of hydrocarbon contaminants on the surface, are well correlated with accumulated irradiance of the 185 nm radiation. The newly developed diamond sensors opened a new path to measure and monitor irradiance from low-pressure mercury lamps as the sensors were also found stable under continuous irradiations from the lamps.

References