*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, O-4.09 (2004)*

In-situ Infrared Cavity Ring-Down Spectroscopy of a capacitively coupled RF Ar/SiH_4 dusty plasma

J.Remy, A.H.F.M.Baede, G.H.J.M.Groothuis, W.W.Stoffels, G.M.W.Kroesen

Applied Physics Dept, Eindhoven University of Technology, Den Dolech 2, 5600 MB Eindhoven, The Netherlands - EU

1. Introduction

Capacitively coupled radio-frequency (rf) argon-silane plasma generate the adequate environment to study the chemical reactions found in solar cell deposition processes. More particularly, radicals inside the plasma are found to be highly reactive in the gas-phase and do sometimes lead to the formation of dust particles. The influence of those particles on the deposition processes is twofold: they not only prove to be harmful to the depositing device [1] but can also improve the stability of the solar cells when they are embedded in certain silicon layers [2]. Laboratory studies all over the world [3,4] have been studying those particles but little is still known about their growth mechanism and transport. Our experiments aim at enriching the diagnostics panel available in the hope of ultimately optimizing the solar cell yield. Cavity Ring-Down Spectroscopy (CRDS) has been foreseen for its high-resolution measurements. It can help determine gaseous reactions products and absolute densities of radicals. It thus represents an extremely valuable tool for the understanding and the study of gas-phase chemical reactions in a rf argon-silane (5% SiH_4 diluted in 95% Ar) plasma discharge.

2. Experimental procedures

The experiments have been performed in a 13.56-MHz capacitively coupled rf plasma generated between two stainless-steel electrodes mounted in a stainless-steel vacuum vessel. To allow for high-resolution spectroscopy, a high-finesse Fabry-Pérot (FP) optical cavity, the CRDS cavity, is coupled to the vacuum vessel. The experimental set-up has been described in detail elsewhere [5]. Note that the FP cavity length can be scanned with a piezoelectric translator mounted on the entrance mirror. The beam of a continuous-wave tunable infrared diode laser system is directed through a mode selector towards the optical cavity and the plasma volume. The laser light leaving the CRDS cavity is focused on an infrared detector whose signal is then amplified and filtered before reaching an analog signal recorder. When the light detected reaches certain intensity, an electronic trigger pulse is generated that starts the signal recorder and simultaneously prevents the laser from sending any further light into the cavity. The latter is achieved by detuning the laser for several tens of microseconds [5]. This results in an exponential decay of the light emerging from the cavity, providing valuable information on the absolute losses occurring within the plasma volume.

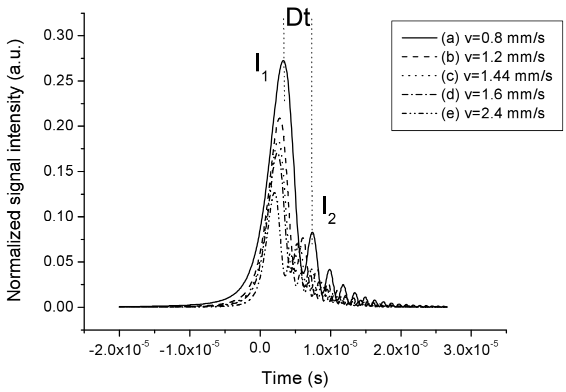
3. CRDS cavity simulation results

A model based on one-dimensional Fabry-Pérot analytical equations has been used to simulate the output electric field measured outside the FP cavity:

$$E_{out}(t) = (1-r^2)\sum_{n=0}^{\infty} r^{2n} E_{in}(t-(n+\frac{1}{2})t_r)\exp -j\left(\left(\sum_{m=0}^{n}\delta(t-\frac{t_r}{2}-mt_r)\right)-\frac{\delta}{2}(t-\frac{t_r}{2})\right) \quad (1)$$

One can see from (1) that the FP transmission seems to depend on two factors, namely the scanning speed and the reflectivity of the cavity mirrors (r), the latter being studied in [5]. A more thorough analysis of the simulation results should help us determine to which extent the scanning speed also influences the cavity's behavior.

Using (1), we simulate our cavity at the monochromatic wavelength λ=5 µm, close to the absorption lines of SiH_x radicals. The cavity is one meter long and its entrance mirror is moved by the piezoelectric translator. The mirrors' field reflectivity is r=0.9995. Fig. 1 shows the relative transmitted intensity for various mirror velocities, as the mirror moves through resonance. The input beam is in resonance with the cavity at t=0. The light source is not interrupted, but the rise and fall of the transmitted light is due to the cavity moving through resonance.



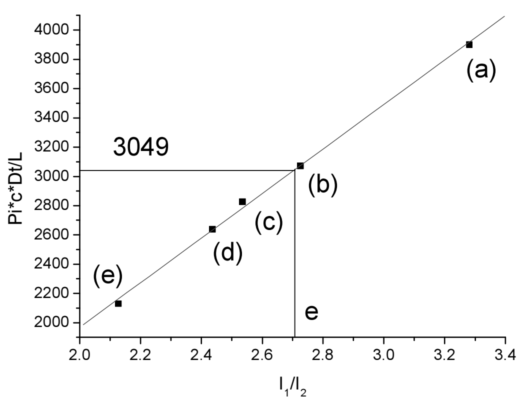


Fig.1 (left): Relative intensity being transmitted through the FP cavity as a function of the mirror's speed (r=0.9995). Photons keep being injected into the cavity. Some oscillations become more visible as the transducer speed gets higher from curves (a) to (e). I_1 and I_2 are the first two maxima of each Airy peak and Dt the time delay between them.

Fig. 2 (right): Simulated evolution of $\pi c\Delta t/L$ as a function of the ratio I_1/I_2, which is obtained from the different evolutions of the FP cavity transmission versus time simulated in fig.1: (a) Δt=4.14 μs and I_1/I_2=3.28 >e (b) Δt=3.26 μs and I_1/I_2=2.72 ≅e; (c) Δt=3 μs and I_1/I_2=2.54 <e; (d) Δt=2.80 μs and I_1/I_2=2.44 <e; (e) Δt=2.26 μs and I_1/I_2=2.13 <e. The solid linear fit leads to F_{sim}=3049.

Obviously, the time necessary for light to build up inside the cavity until resonance occurs at t=0, i.e. the ring-up time, decreases whenever the scanning speed increases. Moreover, the slower you move the mirror, the longer the FP is in resonance, the more light can be injected into the cavity before being decoupled so the absolute intensity also increases with decreasing velocity. These observations concur with numerical predictions that were obtained by Poirson et al [6] in a similar work.

The oscillations seen on the Airy peaks can also be exploited [6] to lead to the cavity finesse (*F*), i.e. the quality of the resolution that can be obtained with the cavity. Based on the ratio of the first two maxima I_1/I_2 of each Airy peak and the time delay Δt between these maxima (see fig.1), the analytical equation (2) can be written:

$$\frac{\pi c\Delta t}{L} = \frac{F}{2}\left(\frac{I_1}{I_2} + 2 - e\right) \quad (2)\ [6]$$

Using the simulated profiles from fig.1, the evolution of $\pi c\Delta t/L$ as a function of the ratio I_1/I_2 can be drawn on fig.2. A linear fit provides with a value for the cavity finesse F=3049.

The theoretical finesse (F_{th}) of a FP cavity is more commonly described as a function of the mirrors' reflectance R, as written in (3):

$$F_{th} = \pi\frac{\sqrt{R}}{1-R} = \pi\frac{\sqrt{r^2}}{1-r^2} \quad (3)\ [7]$$

Considering r=0.9995 in (3), we obtain F_{th}= 3140, which is consistent with the value of F obtained previously. The simulation thus provides a relatively good precision over the cavity finesse of the order of 3%, leading to: F=3049 ± 88

Notice that the linear fit of fig.2 is linear with a slope equal to F/2, as expected from (3). This tends to validate our numerical simulation.

4. CRDS preliminary experimental results

Carbon monoxide (CO) has a rovibrational spectrum, which coincides very well with the silane and the silane radicals wavelength region. Moreover, this spectrum is well documented in the infrared wavelength range [8] and provides accurate absorption lines. CO is therefore of particular interest for our investigation and can help demonstrate the relevance of the CRDS in a silane plasma study. Let us furthermore emphasize that, to the best of our knowledge, CO has never been studied in the mid-infrared using the CRDS technique.

Fig. 3 shows a spectroscopic cavity ring-down measurement that was performed on CO. The vacuum vessel was filled with 7.5 mTorr CO and the laser diode was scanned through the $C_{12}O_{17}$ line, which lays around 2147.20497 cm^{-1}. Note that the signal to noise ratio limits our absorbance detection ability to $5x10^{-5}$. Such a figure proves that performing CRDS experiments with a CW laser diode and a tunable confocal cavity does work and provides good sensitivity.

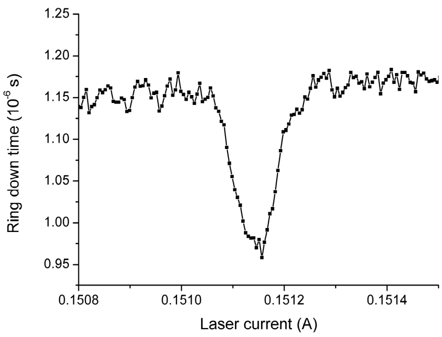


Fig.3: Spectroscopic ring-down measurement performed on CO. The laser diode is scanned through the $C_{12}O_{17}$ line. The signal to noise ratio limits our absorbance detection range to $5x10^{-5}$. Absorption is clearly visible through the drop in the ring-down time.

References

[1] G. S. Selwin, J. S. McKillop, K. L. Haller, J. J. Wu, J.Vac.Sci.Technol.A, Vol. 8 (1990)

[2] P. Roca I Cabaroccas, P.St'ahel, S. Hamma, Y. Poissant, Proc. 2nd world conference on photovoltaic solar energy conversion, Vienna (1998).

[3] A. Bouchoule, A. Plain, L. Boufendi, J. Ph. Blondeau, C. Laure, J.Appl.Phys., Vol. 70, No.4 (1991)

[4] W. W. Stoffels, E. Stoffels, Trends in Vacuum Science and Technology, Vol. 4 (2001)

[5] J. Remy, M. M. Hemerik, G. M. W. Kroesen, W. W. Stoffels, IEEE Trans. Plasma Sci., accepted for publication (2004)

[6] J. Poirson, F. Bretenaker, M. Vallet, A. Le Floch, *J. Opt. Soc. Am. B*, Vol.14, No.11 (1997).

[7] K. W. Busch, M. A. Busch, *American Chemical Society*, Washington DC, ch. 2, (1999)

[8] G. Guelachvili, K. Narahari Rao, *Academic Press*, London, 1986