In-situ Infrared Cavity Ring-Down Spectroscopy of a capacitively coupled 
RF Ar/SiH$_4$ dusty plasma


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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:

\[ E_{\text{out}}(t) = (1-r^2)\sum_{n=0}^{\infty} r^{2n} E_n(t-(n+\frac{1}{2})\tau) \exp\left(-\frac{(\sum_{n=0}^{\infty} \delta t - t - \frac{1}{2})}{2}\right) \]  \hspace{1cm} (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 \( \lambda = 5 \) μm, close to the absorption lines of SiH₅ 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...](image)
transducer speed gets higher from curves (a) to (e). \( I_1 \) and \( I_2 \) are the first two maxima of each Airy peak and \( \Delta t \) 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) \( \Delta t=4.14 \ \mu s \) and \( I_1/I_2=3.28 >e \) (b) \( \Delta t=3.26 \ \mu s \) and \( I_1/I_2=2.72 \approx e \); (c) \( \Delta t=3 \ \mu s \) and \( I_1/I_2=2.54 <e \); (d) \( \Delta t=2.80 \ \mu s \) and \( I_1/I_2=2.44 <e \); (e) \( \Delta t=2.26 \ \mu s \) and \( I_1/I_2=2.13 <e \). The solid linear fit leads to \( F_{\text{sim}}=3049 \).

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 \( \Delta t \) between these maxima (see fig.1), the analytical equation (2) can be written:

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

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):

\[
F_{th} = \pi \sqrt{\frac{R}{1-R}} = \pi \frac{\sqrt{r^2}}{1-r^2} \tag{3} [7]
\]

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: \( F=3049 \pm 88 \)

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.

![Graph showing spectroscopic ring-down measurement on CO.](image)

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