# Dynamics of deposition and removal of a fluorocarbon film in the cyclic process of plasma-chemical etching of silicon

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## 1. Introduction

Deep reactive ion etching (DRIE) of silicon is a key process in MEMS and 3D-IC technologies. The key challenges of DRIE are to achieve high aspect ratio (HAR) trenches with smooth, usually vertical, sidewall profiles, obtain high etch rate and selectivity. Among the various DRIE processes, Time-Multiplexed Deep Silicon Etching (TMDSE) is the fastest process which alternates etching step (fast, isotropic removal of Si) and deposition step (sidewall etch inhibition with polymer). One of the solutions to improve HAR etch performance is independent optimization of the polymer removal at the beginning of the etching step by introduction of the third step in between the deposition and the etching [1-5].

In this paper *in situ* measurements of the dynamics of deposition and etching of a fluorocarbon film (FCF) during three-step TMDSE process using a laser interferometer have been carried out. Direct measurements of the deposition and etch rates, as well as the etch time of the FCF, open up new possibilities for optimizing the cycle procedure. For example, adjusting the etching time of the FCF improves the selectivity of the etching process (etch rate of silicon divided by the erosion rate of $SiO_2$ mask).

## 2. The three-step TMDSE procedure

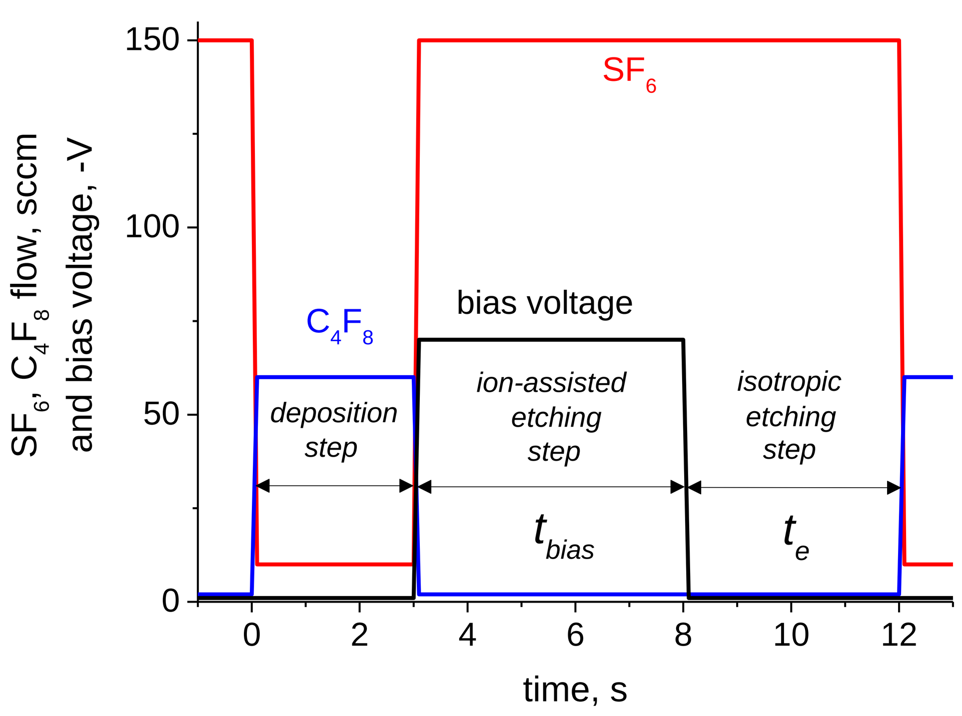



***Fig. 1*** *TMDSE parameters and etch sequence. The flow rate of SF6 during the deposition step varies from 8 to 12 sccm.*

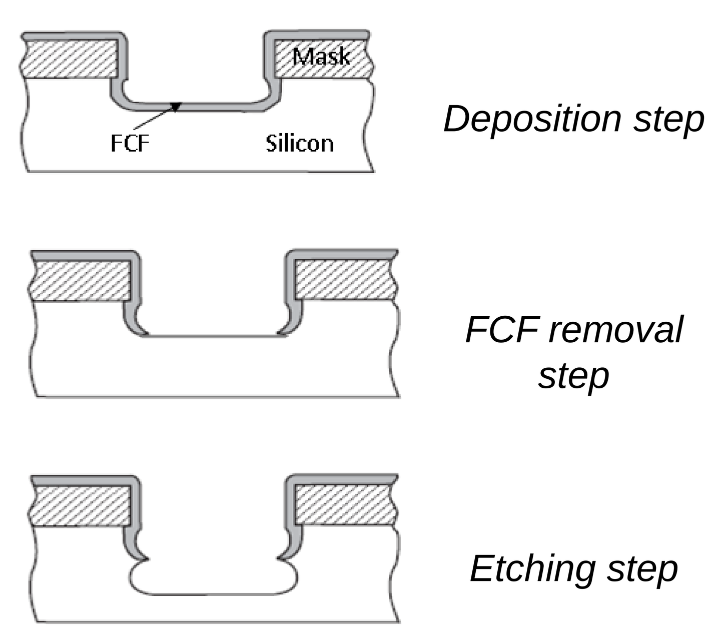



***Fig. 2*** *The TMDSE principle of anisotropic etching of the HAR trench.*

The initial portion of the etching step, at which the polymer is removed at the trench bottom, plays a very important role influencing the trench profile and selectivity.

## 3. Experiment

Experiments were performed by a laser interferometer (λ=633 nm) with a double-beam scheme from Sofie Instruments. The reflection of the measuring beam from a continuous SiO2 film (~1 µm thick) on silicon was used. The dynamics of cyclic switching of the gas flow from $SF_6$ to $C_4F_8$ during TMDSE was synchronized with the process of recording the reflection intensity (I).

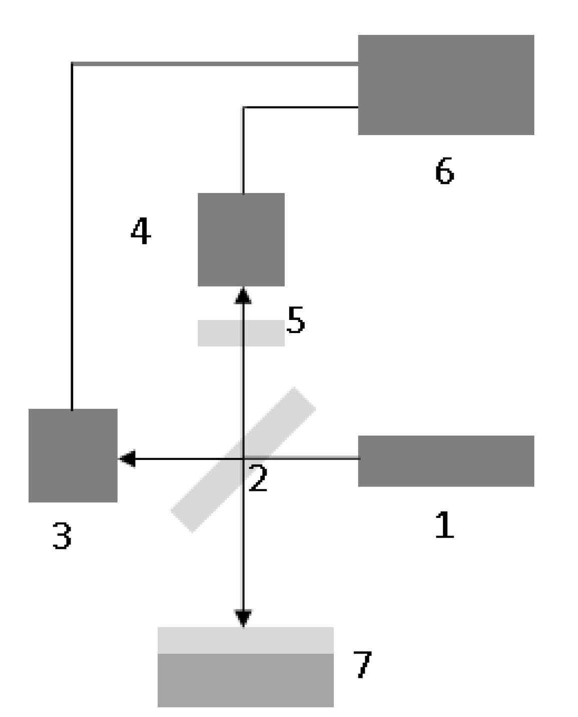


***Fig. 3*** *Interferometer design: 1-He-Ne laser, 2-beem splitter, 3,4-photodetectors, 5-filter (633 nm), 6-software and hardware module.*

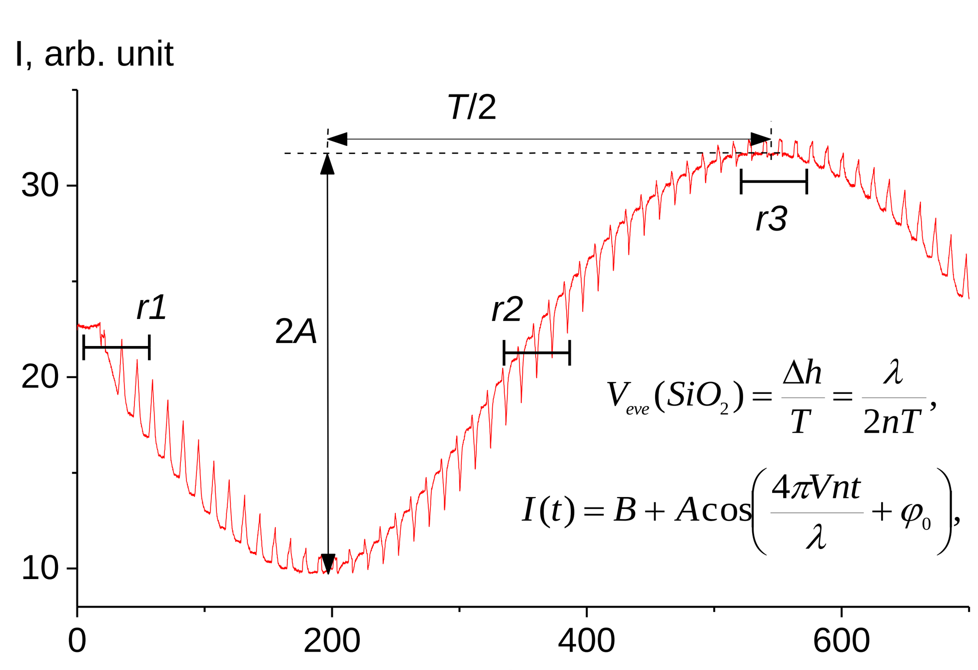



***Fig. 4*** *Partial etch trace of the ~200 nm silicon dioxide layer.*

$$V \approx \frac{\Delta I}{\Delta t}\frac{\lambda}{4\pi An},$$ *etch and deposition rate in cycle*

*Calculation of ΔI/Δt in intervals r1 or r2*

In the interferometer signal during TMDSE etching, cyclic (with a period of 12 s) oscillations of intensity are observed, associated with a change in the optical thickness of the two-layer structure - FCF on SiO2.

## 4. Study of deposition and etching processes in a cycle

FCF removal time ($t_r$) determination

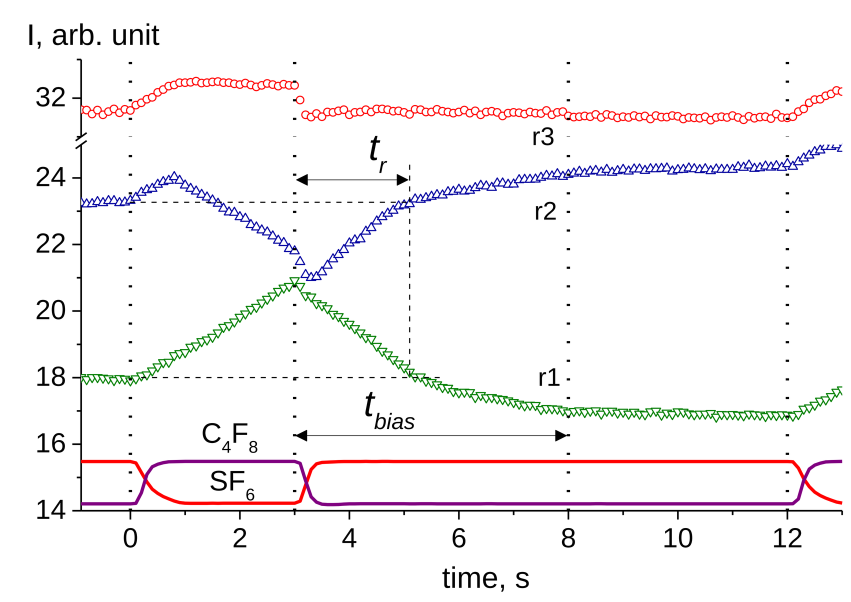



***Fig. 5****. Reflectivity during one TMDSE cycle at different trace intervals (Fig. 4) and the measured dynamics of gas flow switching.*

Result of smoothing dI/dt (interval **r2**)

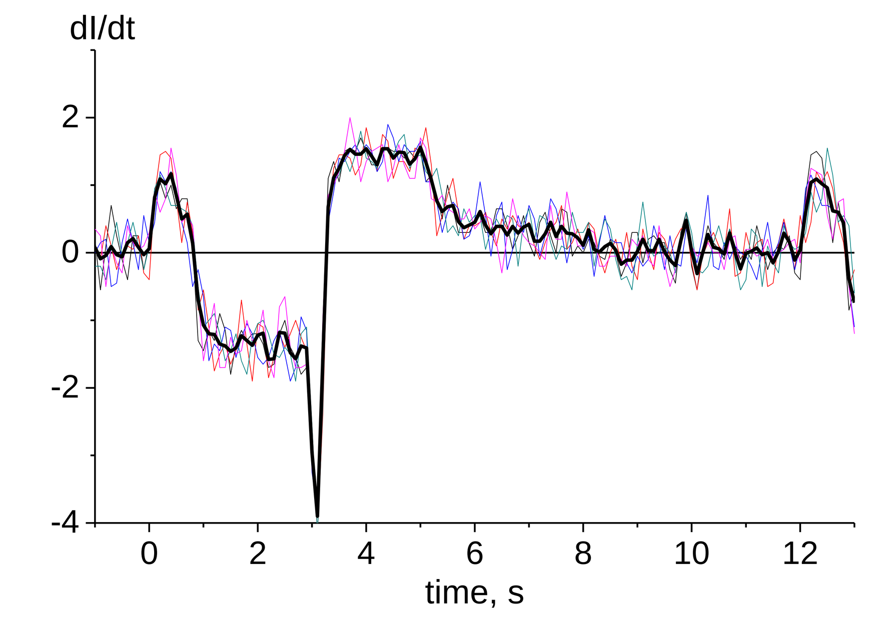



***Fig. 6****. Calculated values of dI/dt according to the dependence I(t) for five cycles. The black line is the result of averaging.*

*The different radiation power of the SF6 and c-C4F8 plasmas at the laser wavelength affects the shift of the interferometer signal when the gas flow is switched.*

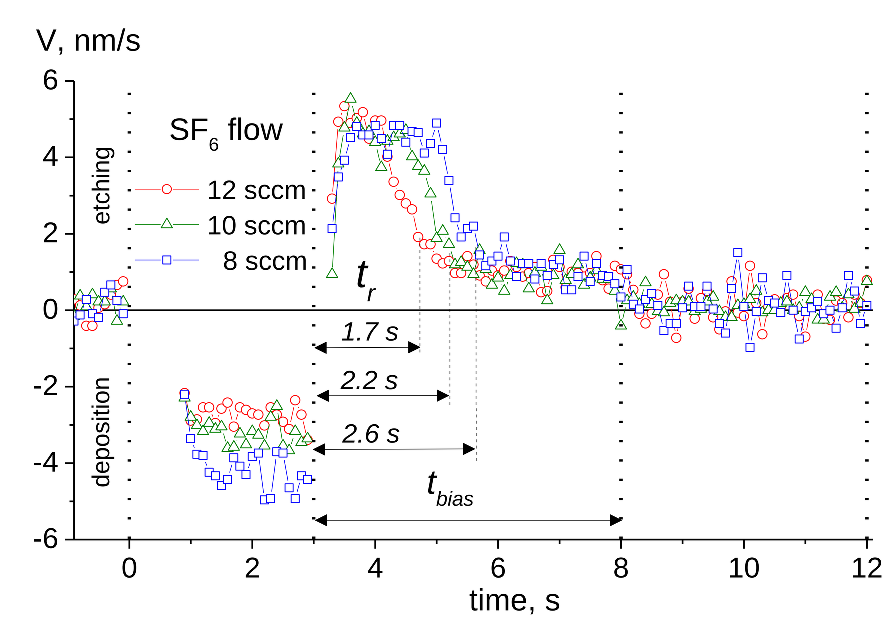



***Fig. 7****. Calculation results of deposition and etching rates in cycle for three TMDSE processes*

| Q(SF6), sccm | 12 | 10 | 8 |
|---|---|---|---|
| Deposition rate, nm/s | 2.7 | 3.2 | 4.3 |
| FCF removal time, s | 1.7 | 2.2 | 2.6 |

| FCF etching rate | $SiO_2$ etching rate with bias | $SiO_2$ etching rate without bias |
|---|---|---|
| | $V_{bias}$ | $V_0$ |
| 4.7 nm/s | 0.95 nm/s | 0.15 nm/s |

$$V_{eve}(SiO_2) = \frac{V_{bias}(t_{bias} - t_r) + V_0 t_e}{t_c},$$

## 5. TMDSE optimization and Conclusions

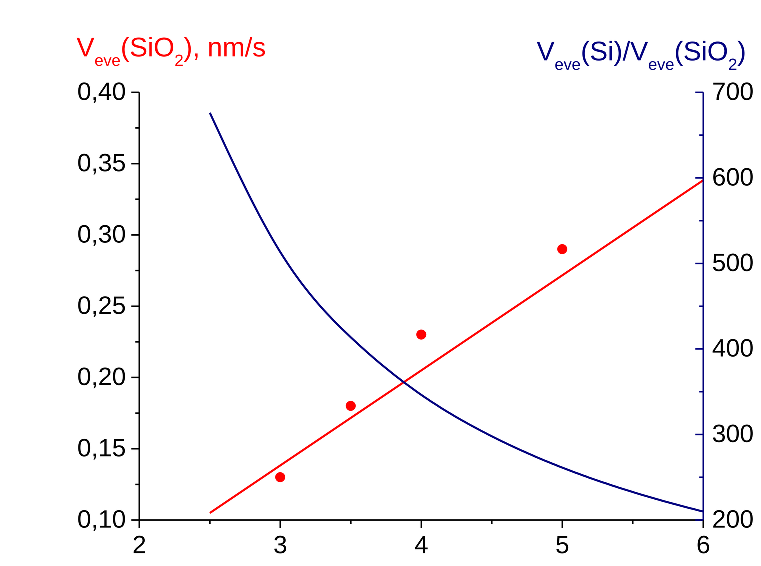
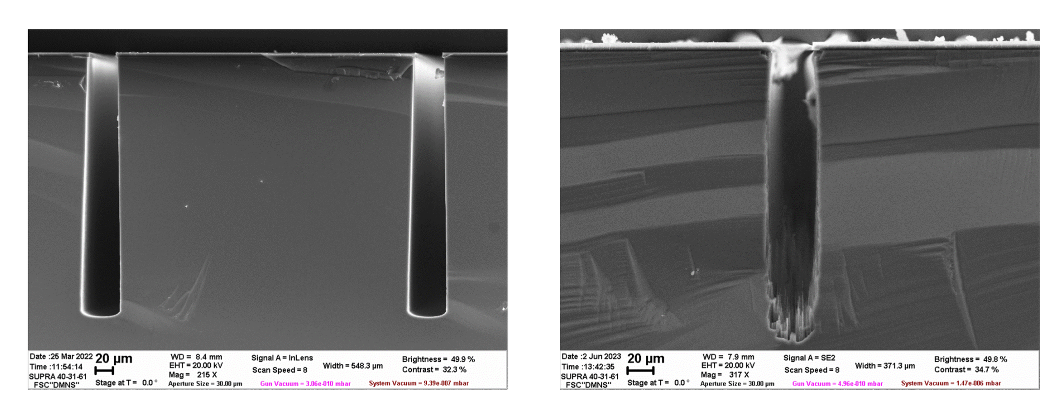



***Fig. 8.*** *The average oxide etching rate and selectivity as a function of t $_{bias}$ at $t_r$ =2.2 s.*

*Red line* – calculation rate from measured values: $V_{bias}$, $V_0$, $t_r$.

*Red dot* – calculation rate from measured values: *T.*

*Blue line – selectivity.*



| Q(SF6)=10 sccm | Q(SF6)=8 sccm |
|---|---|
| $t_r$ =2.2 s, $t_{bias}$=3 s | $t_r$ =2.6 s, $t_{bias}$=3 s |
| $t_{bias}/t_r$ =1.35 | $t_{bias}/t_r$ =1.15 |
| Trench width = 30 µm | Trench width = 30 µm |
| Trench depth = 298 µm | Trench depth = 227 µm |
| Straight profile | Etching stops with the formation of grass at the bottom of the trenches |
| Sidewall angle = -1° | |

***Fig. 9.*** *SEM images of trenches after 300 TMDSE cycles ($t_{bias}$=3 s).*

✓The presented studies open up new possibilities for using the laser interferometer to develop reliable TMDSE processes.
✓The FCF etch time measurement allows you to fine-tune the removal step to achieve a quality trench profile with a highly selective etch process.
✓The demonstrated measurement capabilities are useful for evaluating the stability of TMDSE conditions in industrial etching reactors.

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