Study and optimization of PECVD films containing fluorine and carbon as ultra low dielectric constant interlayer dielectrics in ULSI devices

Nandini Sundaram
KLA-Tencor Corp., One, Technology Drive, Milpitas, California 95035

Gil Sik Lee
Department of Electrical Engineering, University of Texas at Dallas, 800 W Campbell Road, Richardson, Texas 75080

Matthew Goeckner
Department of Mathematics, University of Texas at Dallas, 800 W Campbell Road, Richardson, Texas 75080

Lawrence J. Overzet
Department of Electrical Engineering, University of Texas at Dallas, 800 W Campbell Road, Richardson, Texas 75080

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Fluorinated amorphous carbon films that are thermally stable at 400°C have been deposited in a plasma enhanced chemical vapor deposition system using tetrafluorocarbon and disilane (5% by volume in helium) as precursors. The bulk dielectric constant (k) of the film has been optimized from 2.0/2.2 to 1.8/1.91 as-deposited and after heat treatment, by varying process parameters including power density, deposition temperature, and wall temperature. Films, failing shrinkage rate requirements, possessing promising k-values have been salvaged by utilizing a novel extended heat treatment scheme. Film properties including chemical bond structure, F/C ratio, refractive index, surface planarity, contact angle, dielectric constant, flatband voltage shift, breakdown field potential and optical energy gap have been evaluated by varying process pressure, power, substrate temperature, and flow rate ratio of processing gases. Both x-ray photoelectron spectroscopy and FTIR results confirm that the stoichiometry of the ultralow k film is close to that of CF2 with no oxygen. C-V characteristics indicate the presence of negative charges that are either interface trapped charges or bulk charges. Average breakdown field strength was in the range of 2–8 MV/cm while optical energy gap varied between 2.2 and 3.4 eV.

I. INTRODUCTION
A. Integration challenges and desired properties of ultralow k materials

The 2013 update to the International Technology Roadmap for Semiconductors roadmap details one of the difficult challenges for >22 nm node as the introduction of new dielectric materials to meet conductivity challenges and reduce dielectric permittivity.1 For the 10 nm node, materials with k-values between 2.4 and 2.5 may still be utilized while retaining currently used integration scheme. However, a materials solution for the sub-7 nm node, which requires materials with a k value of 2.2, is not yet available.2

Reduction in delay times, overall power consumption, and parasitic intermetal capacitances provide the motivation to research newer materials and interconnect schemes and lower the capacitance of back-end-of-line structures. With continuous shrinkage of device dimensions, interconnect delays become significant in comparison to transistor performance delays in ultralarge scale integrated devices. Since continuous reduction in metal linewidths leads to increased metal line resistances and the constant shrinkage of the distance between metal lines results in increased parasitic intermetal capacitance,3 the decrease in capacitance (C) values achieved by lowering dielectric permittivity is significant to lower delay times.

In the past, attempts to evaluate amorphous fluorocarbon (a:C-F) and fluorinated DLC films separately, for low-k dielectric applications,4–8 have not been successful. For a:C-F, even though k-values as low as 1.3 have been achieved in the as-deposited state,9 once the films are annealed, F outgassing not only leads to high shrinkage rates but also poses difficulties in maintaining a sufficiently low k-value10 (Table I). In the case of fluorinated DLC with k-values less than 2.5, reactions with SiO2, SiN, and TaN at 400°C result in film instability, even after instituting stabilization treatments, due to the formation of Si–F and Ta–F bonds.13 Therefore, optimizing each film separately and subsequently depositing these films as layers rather than mixtures provides a potential solution to overcome limitations due to F reactivity.14

B. a:C-F deposition

Previously we have demonstrated the applicability of a:C-F films deposited using CF4 and Si2H6 for low-k dielectric applications.15 In this work, film properties are changed by substantially modifying the reactor chamber configuration to allow for the use of larger gas volumes and gas flow rates.
(by almost a factor of 10) while maintaining similar operating pressures. Residence time of radicals is given by
\[
\tau = PV / f,
\]
where \( \tau \) is the residence time of radicals, \( P \) is the process pressure, \( V \) is the process volume, and \( f \) is the flow rate of precursor gases. Chamber dimensions play an important role in densities of CF\(_2\), CF\(_3\), and other gas phase constituents especially at higher self-bias voltages.\(^{16}\)

A 50% reduction in CF\(_4\) densities with a change in wall temperature from 60°C to 30°C has been observed. Assuming that both adsorption and desorption plasma wall interactions occur, it is reasonable to expect that higher wall temperature would impart larger thermal energy to CF\(_4\) radicals substantially affecting the plasma core. Since sticking coefficients are typically lower with increasing temperatures CF\(_4\) concentration is increased by decreasing the impact of an important loss mechanism. For this reason, heated chamber walls (60°C) are utilized during deposition.

The CF\(_4\)-Si\(_2\)H\(_6\) plasma system comprising the scheme of Yasuda \textit{et al.}\(^{17}\) modified to include the role of fluorine trapping agents and deposition mechanisms has been detailed elsewhere.\(^{15}\) Some possible reactions for the interaction of electrons with CF\(_4\) include

\[
e^- + CF_n \rightarrow CF_n^* + e^-,
\]

\[
CF_n^* \rightarrow CF_{n-1}^* + F^-
\]

or

\[
e^- + CF_n \rightarrow CF_{n-1}^* + F^+,
\]

\[
e^- + CF_n^* \rightarrow CF_{n-1}^++F + 2e^-,
\]

where \( X^* \) denotes excited \( X \) and \( X^- \) denotes a free radical. Helium atoms, used for precursor dilution, when excited to metastable states can transfer energy to ions or radicals via inelastic collisions. Fluorine trapping reactions include\(^{18}\)

\[
-SiH_{n(surface)} + (4 - n)F^- \rightarrow SiH_nF_{4-n(gas)} ^+,
\]

\[
H^+ + F^- \rightarrow HF_{(gas)} ^+,
\]

and

\[
e^- + -SiH_n + O_2 \rightarrow SiO_2 + nH^+ + (n + 1)e^-.
\]

Finally, a shrinkage rate of less than 5% is an important criterion in the selection of a suitable interlayer dielectric. While depositing films using fluorohydrocarbons, Theil \textit{et al.} observed that the shrinkage rates stabilized after 15 min of annealing.\(^{19}\) A reduction in this rate has also been observed by Grill \textit{et al.} with fluorinated diamondlike carbon films.\(^{13}\) In order to take advantage of this phenomenon, an extended stabilization anneal has been incorporated prior to exploring the optimized process space and evaluating resulting film properties.

\section*{II. EXPERIMENT}

A commercially available plasma deposition tool (UNAXIS 790 SERIES) with electrode diameter of 15 in. was utilized. The top electrode is RF powered (13.56 MHz), and the process chamber wall was maintained at 60°C using a heat exchanger.

Boron-doped p-type (100) Si wafers were cleaned using standard RCA methods before deposition. An initial screening study was undertaken by varying process parameters as shown in Tables \textbf{II} and \textbf{III}. Film thickness, refractive index

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\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Reactor & Current work & Jin \textit{et al.} (Ref. 5) & Kim \textit{et al.} (Ref. 9) & Kim \textit{et al.} (Ref. 11) & Takeishi \textit{et al.} (Ref. 12) & Shieh \textit{et al.} (Ref. 6) \\
\hline
Mixture gas & Si\(_2\)H\(_6\)(5%)/He & Si\(_2\)H\(_6\)(5%)/He & Si\(_4\)H\(_{10}\)(20%)/Ar & Si\(_2\)H\(_6\)(5%)/He & C\(_2\)H\(_2\) or H\(_2\) & CH\(_4\) \\
\hline
Power density (W/cm\(^2\)) & 0.04–0.2 & 0.098–0.59 & — & 0.255 & 0.59 & — \\
\hline
F source flow (sccm) & 500–1200 & 9.3–70.6 & — & 30 & — & 60 \\
\hline
Mixture gas flow (sccm) & 30–100 & 2.3–3.3 & — & 2 & — & 0–17.2 or 50 \\
\hline
Total & 530–1300 & 73 & — & 32 & — & 60–67.2 or 110 \\
\hline
Flow ratio & 5–30 & 21–35 & 15 & 1 & 3.49/1.2 & 5–15 \\
\hline
Ts (°C) & 120–200 & 40–200 & 200 & 25–200 & 250–400 & 50–350 \\
\hline
Process pressure (mTorr) & 300–700 & 300–900 & 495 Pa & 100–800 & 1200 & 300–700 \\
\hline
K & 1.8 & 2.2 & 1.3–2.0 & 2.18 & 1.9 & 2.3 \\
\hline
k (annealed) & 1.9 & 2 & — & — & — & ~2.3 \\
\hline
Shrinkage (optimized film) & 3.30% & ~0% & — & 9.40% & ~0% & <2.0% \\
\hline
Wall temperature (°C) & 60°C & Cold wall & Cold wall & Cold wall & Cold wall & Cold wall \\
\hline
\end{tabular}
\caption{Comparison of current work with similar research.}
\end{table}

---

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Power (W) & Pressure (mTorr) & Temperature (°C) & Flow rate ratio (CF\(_4\):Si\(_2\)H\(_6\)) \\
\hline
50/147 & 300 & 40 & 15 \\
100/196 & 500 & 100 & 18 \\
150/294 & 700 & 160 & 21 \\
200/392 & 900 & 220 & 24 \\
250/490 & — & — & 27 \\
300/588 & — & — & 30 \\
350/686 & — & — & 33 \\
400/784 & — & — & 36 \\
\hline
\end{tabular}
\caption{Screening study.}
\end{table}
(RI), and contact angle with water was measured. Average roughness ($R_a$) and root mean square ($R_{rms}$) values were measured by using the vertical scanning interferometry mode of a profilometer. Relative atomic percentage of fluorine to carbon was measured using energy dispersive x-ray analysis (EDS). GeATR attachment of a ThermoElectron FTIR was utilized to evaluate the chemical bond structure. Films were annealed in Ar ambient using a Thermco MiniBrute tube furnace for $1 \text{ h at } 400^\circ\text{C}$. After thickness and refractive index measurement, they were reannealed using the exact same process and recharacterized.

Metal–insulator–semiconductor capacitors were fabricated for high frequency capacitance–voltage (C-V) measurements and current–voltage measurements (I-V) at room temperature. Three films with ultralow, low, and high $k$-values were evaluated using x-ray photoelectron spectroscopy. The ultralow $k$ (ULK) film was characterized by using a Rigaku Altima III 2000 XRD system (Cu Kα radiation) and SEM. Optical transmission data were obtained using a spectrophotometer. A plain quartz slide was used as a baseline and subtracted.

### III. RESULTS AND DISCUSSION

It is expected that modifying process parameters results in changes to bonding configuration and chemical composition of the film. In turn, these strongly influence the physical and electrical properties of the film. Apart from the dielectric constant, properties relevant for film integration include shrinkage rate, breakdown (BD) field strength, effective charge density, contact angle, roughness, and optical properties. To this end, where possible, such correlations are explored and detailed in the ensuing discussion with the aim of providing some guidance in understanding the numerous interaction effects that occur in complex plasma space. Where such correlations exist in literature for singly annealed films or films deposited using other precursors or process conditions, and may be extended to our specific system, a short reference to the mechanism associated with previous results is alluded to in order to aid the reader pursue such additional investigation. Finally, a direct structural and compositional comparison of ULK, low-$k$, and high-$k$ films has been undertaken, utilizing complementary techniques of XPS and FTIR to provide an improved understanding of the moieties that results in lowered dielectric constant values.

Only two films subject to the stabilization thermal treatment were subsequently measured to be ULK.

#### A. Shrinkage rate

Incorporating the stabilization treatment is successful since shrinkage rates, of the order of $40\%-60\%$, decrease to values between $2\%$ and $5\%$ after the extended thermal annealing process (Fig. 1). Shrinkage rates from the first and second anneal correlate with each other. From IR analysis, it is readily apparent that annealed films exhibit both the growth of bands between $1400$ and $2000$ cm$^{-1}$ and a reduction in CF$\text{x}$ peak intensity. These results are interpreted as an increase in C–C bonds at the expense of fluorocarbon single bonds C–C (Ref. 20) (Figs. 2–4). Our data therefore not only correlate well with increased shrinkage rates observed by several authors with increasing flow rate ratio (FRR), attributed to F outgassing,$^{12,15,17}$ but also confirms that the extended

#### Table III. Final design of experiment.

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Pressure (mTorr)</th>
<th>Temperature ($^\circ\text{C}$)</th>
<th>Flow rate ratio (CF$_4$ : Si$_2$H$_6$)</th>
<th>Total flow (scm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>300</td>
<td>120</td>
<td>5</td>
<td>530</td>
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<tr>
<td>50</td>
<td>500</td>
<td>140</td>
<td>10</td>
<td>540</td>
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<td>100</td>
<td>700</td>
<td>160</td>
<td>12.5</td>
<td>550</td>
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<tr>
<td>150</td>
<td>—</td>
<td>180</td>
<td>16.67</td>
<td>600</td>
</tr>
<tr>
<td>200</td>
<td>—</td>
<td>200</td>
<td>24</td>
<td>840</td>
</tr>
<tr>
<td>—</td>
<td>—</td>
<td>—</td>
<td>25</td>
<td>1000</td>
</tr>
<tr>
<td>—</td>
<td>—</td>
<td>—</td>
<td>30</td>
<td>1240</td>
</tr>
</tbody>
</table>

![Fig. 1](image1.jpg) "Shrinkage rate and F/C ratio with FRR using process conditions: (a) 500 mTorr, 1200 $^\circ\text{C}$, 100 W, (b) 500 mTorr, 1400 $^\circ\text{C}$, 100 W, and (c) 500 mTorr, 1600 $^\circ\text{C}$, 100 W."

![Fig. 2](image2.jpg) "FTIR spectra of (a) as-deposited (As Dep) and (b) annealed for 2 h at 400 $^\circ\text{C}$ (Ann): 500 mTorr, 1200 $^\circ\text{C}$, 100 W and FRR of (a) 12.5, (b) 20, (c) 25, and (d) 30."
treatment does not significantly modify the annealing mechanism or film structure. An interesting deduction is that at FRR 12.5, film densification results in higher residual thickness\(^6\) when process power is increased from 50 to 100 W. Standard forming gas anneal (NH\(_3\)/H\(_2\)) done at 400°C for 1 h resulted in film degradation via blister formation.

### B. k-value

The relationship between k-value and refractive index \((n)\) and the variation of film k-value with FRR, pressure, temperature, and power has been studied in detail. The lack of a direct dependence between \(k\) and \(n\) (Fig. 5) correlates well with FTIR data that reveal the presence of the bending mode of Si-O at 808 cm\(^{-1}\) (Ref. 20) and Si–F\(_n\) bonds between 820 and 980 cm\(^{-1}\).\(^21\) It has been previously observed that high refractive films with the same F content could have differing \(k\) values due to variation in film crosslinking, density, hydrogen incorporation, and structure.\(^12\)

\(k\) value in general decreases with increasing FRR (see Fig. 6) due to the increasing Teflon-like nature of the film. IR spectrum reveals the presence of a primary broad peak between 900 and 1400 cm\(^{-1}\) corresponding to random arrangements of the CF\(_x\) group (CF, CF\(_2\), and CF\(_3\)) with a shoulder at 980 cm\(^{-1}\) (C–F bond vibrations). While the peak at 1220 cm\(^{-1}\) corresponding to CF\(_2\) asymmetric stretching mode becomes sharper with higher FRR, peaks corresponding to double bonds (C=C, CF\(_2\)=C, or CF\(_2\)=CF) or oxygen related peaks (C–O or Si–O) are completely absent. At FRR = 20, two peaks at 1260 and 1100 cm\(^{-1}\) corresponding to the doublet in bulk polytetrafluoroethylene (PTFE) are distinguished and the band at 740 cm\(^{-1}\) is also characteristic of highly cross-linked, amorphous PTFE.\(^22\)

\(k\) increases slightly with decreasing pressure,\(^23\) due to increased Si and oxygen incorporation and film structure modification. The strong peak at 1220 cm\(^{-1}\) observed at 500 mTorr corresponding to CF\(_2\) shifts to 1050 cm\(^{-1}\) at 300 mTorr with a stronger CF component\(^24\) (Fig. 4). Bands corresponding to Si–O (Refs. 8 and 9) and Si–F (Ref. 25) appear at lower pressures indicating a structural change. \(k\) value decreases with increasing power for FRR of 12.5, and at the low setting for power of 40 W, FTIR data confirms that oxygen incorporation results in higher \(k\) values.

After annealing, the general trend indicates that \(k\)-value increases due to conversion of C–C to C=\(\equiv\)C bonds and

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**Fig. 3.** FTIR absorption spectra between 700 and 2000 cm\(^{-1}\) of (a) as-deposited (As Dep) and (b) annealed for 2 h at 400°C (Ann) deposited using process conditions 500 mTorr, 100 W, FRR 30, TF 1240 sccm and temperatures (a) 200°C, (b) 180°C, (c) 160°C, (d) 140°C, and (e) 120°C.

**Fig. 4.** FTIR absorption spectra of (a) as-deposited (As-Dep) and (b) annealed for 2 h at 400°C (Ann) deposited using process conditions FRR 12.5, TF 540 sccm, 120°C, 100 W and (a) 300 mTorr and (b) 500 mTorr.

**Fig. 5.** (a) FTIR spectra: 500 mTorr, 160°C, FRR 12.5, TF 540 sccm and power 50 and 40 W. (b) Variation of \(k\) with refractive index: (i) as-deposited film (As dep) and (ii) annealed films (Ann).
removal of F and H attached to C, resulting in the formation of a more open network (Figs. 6 and 7).

C. VFB, effective charge density, and average breakdown field strength

Flatband voltage is calculated using depletion capacitance based on the Mott–Schottky relationship. Sweeping from $+V_G$ to $-V_G$ results in these curves shifting to the left, indicating the presence of trapped rather than mobile charges. Effective charge density is also calculated and found to be of the order of $10^{13}/\text{cm}^2$. At electric field strength of 1 MV/cm, current density varies between $10^{-6}$ and $10^{-9}$ A/cm². By comparing structural and compositional data for films deposited using various temperatures [Fig. 7(c)], it can

Fig. 6. (Color online) (a) DR, RI, and F/C ratio with FRR (i) 700 mTorr, 160°C, 50 W; (ii) 700 mTorr, 160°C, 100 W; (iii) 500 mTorr, 120°C, 100 W; (iv) 500 mTorr, 140°C, 100 W; (v) 500 mTorr, 160°C, 40 W; (vi) 500 mTorr, 160°C, 50 W; and (vii) 500 mTorr, 160°C, 100 W. (b) k, average BD field strength and composition with FRR for As deposited (As Dep) and annealed (Ann) films: 500 mTorr, 100 W: (i) 160°C, (ii) 140°C, and (iii) 120°C.

Fig. 7. (Color online) k, average BD field strength and composition with temperature: 500 mTorr, 100 W and (a) FRR 12.5, (b) FRR 20, and (c) FRR 30 for As deposited (As Dep) and annealed (Ann) films.

Fig. 8. (Color online) Effect of processing temperature on (a) $V_{FB}$ shift, (b) J-E characteristics, and (c) average breakdown field strength: 500 mTorr, FRR 30, 100 W and (a) 200°C, (b) 180°C, (c) 160°C, (d) 140°C, and (e) 120°C as deposited (As Dep) and after annealing (Ann).
be determined that the average breakdown potential [Fig. 8(c)] follows the F/C ratio trend. Hence, it becomes clear that electrical properties are significantly influenced by structure and composition variations resulting from variation in process parameters. Film deposited using process conditions of 500 mTorr, 120°C, 100 W FRR 30 kAs-deposited = 1.79 kannealed = 1.91 (referred to as ULK from here on) has subsequently been evaluated in detail (Table IV).

D. Contact angle and roughness

Surface energy and roughness influence wettability and adhesion, both of which are important properties required for subsequent processing postdielectric deposition. The average contact angle is at 64° in comparison to the static contact angle measured on Teflon at 108.25°. All films show smooth morphology when viewed under the SEM (Fig. 9). Contact angle at 160°C, FRR 30 shows an abrupt dip consistent, in this case, with higher C content. Overall, $R_a$ is less than 10 nm and $R_z$ is less than 100 nm, indicating a uniform and planar surface. All films also pass the tape test.

E. Optical properties

Films show good transparency of over 90% in the visible range but not in the UV regime (Fig. 10). Film deposited at 300 mTorr has lower transmittance compared to that at 500 mTorr likely due to the presence of Si–O and Si–F bonds. Absorption coefficient exhibits a nonlinear region related to disorder in the network at $\alpha < 10^4 \text{cm}^{-1}$ and linear Tauc region at $\alpha > 10^4 \text{cm}^{-1}$. Optical energy gap increases from 2.4 to 3.4 with increasing FRR and from 2.2 to 2.4 with increasing pressure.

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**Fig. 9.** (a) SEM micrograph: 500 mTorr, 120°C, 100 W and FRR 25 at a magnification of x230. (b) Roughness and contact angle with water with temperature: 500 mTorr, 100 W and FRR (a) 20 and (b) 30.

**Fig. 10.** (Color online) (a) Transmittance, (b) absorption coefficient, (c) $(\alpha E)^{1/2}$, and (d) optical energy gap with wavelength: 500 mTorr, 1200°C, 100 W and (A) FRR 12.5, (B) FRR 25, (C) FRR 30, and (D) 300 mTorr, 1200°C, 100 W FRR 12.5.
F. X-ray diffraction

XRD data confirm that the ULK film is completely amorphous with none of the crystallinity or ordered CF$_2$ bonds found in PTFE [Fig. 11(c)]. This is desirable since crystallinity aids electron transport and creates differential expansion.

G. Comparison of structure and composition in ULK, low-k, and high-k films: FTIR and XPS analyses

XPS spectra were collected from three film categories—ULK, low-k, and high-k (Fig. 12). ULK and low-k samples exhibit higher F/C ratios and lower O$_2$ content compared to the high-k sample. Considering area fractions of deconvoluted components, the high-k film has a smaller percentage of fluorinated specie (CF$_2$ and CF$_3$ moieties) and a larger percentage of C bonded directly to another C atom or H. Additionally, the area percentages of sp$^3$ C in CF$_2$ (14.3%) and C attached to CF$_3$ (60%) is much higher for the ULK as compared to a domination of sp$^2$ carbon in CF type components (80%) for low-k material. F/C ratio of the ULK film at 1.7 is lower than that of PTFE, but both the refractive index at 1.39 and k at 1.8 are comparable.

To determine constituent peaks, the FTIR spectrum of the ULK film is deconvoluted (Fig. 11) by synthetically sharpening the “effective trace bandwidth features.” The principal band splits into nine absorbance bands of which four are attributed to CF type bonds, two to CF$_2$, and the others to CF$_3$, CF–CH$_3$, and CH$_3$, respectively. Of significance in the bonding configuration is the absence of a sharp peak at 1100 cm$^{-1}$ that is an overlap of C-O/Si-O stretching mode and C-F$_x$ group signifying the resulting lack of detectable oxygen incorporation into the film. Both complementary techniques of XPS and IR confirm that CF$_2$ is the primary monomer in the ULK film.

IV. SUMMARY AND CONCLUSIONS

Plasma enhanced chemical vapor deposition process parameters have been optimized to yield a:C-F films with relative dielectric constant of 1.8/1.9 (as deposited and after extended anneal). The breakdown field strength determined from J-E characteristics is 4.2 MV/cm before and after annealing, and leakage current is of the order of $10^{-6}$ A/cm$^2$. Deposition rates (DRs) for as deposited low-k films are between 5 and 7.5 nm/min. FTIR and XPS studies of ULK and high-k samples indicate that CF$_2$ is the primary constituent of the film. XRD spectrum does not reveal any crystallinity in the sample and SEM micrographs indicate smooth morphology. While the shrinkage rate after the first anneal is around 65%, an extended stabilization anneal leads to acceptable shrinkage rates of less than 3%. After the first anneal FTIR spectra reveal the presence of the PTFE doublet and formation of C=C bonds with no changes after extended heat treatment. Optical energy gap, $R_a$, $R_z$, and contact angle of the ULK film is 3.4 eV, 9 nm, 50 nm, and 64$^\circ$.

<table>
<thead>
<tr>
<th>Peak no.</th>
<th>Binding energy (eV)</th>
<th>Functional groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>a,b (Ref. 18)</td>
<td>283, 285</td>
<td>–C–C, –C–H or –C–H$_n$</td>
</tr>
<tr>
<td>d,e (Ref. 3)</td>
<td>289</td>
<td>–CF$_2$–CF$_2$–, –CF–CF$_2$–</td>
</tr>
<tr>
<td>f (Refs. 3 and 10)</td>
<td>290</td>
<td>–CF$_2$–CF$_2$–, –CF–CF–CF$_2$–</td>
</tr>
<tr>
<td>g,h,i (Refs. 3 and 10)</td>
<td>293</td>
<td>–CF$_2$–, CF$_2$–CF$_2$–, CF$_3$–CF$_2$–</td>
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<tr>
<td></td>
<td>294</td>
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<td></td>
<td>296</td>
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</tbody>
</table>

Fig. 11. (Color online) (a) Original and (b) synthetic FTIR spectra: 500 mTorr, 120$^\circ$C, 100 W, FRR 30, TF 1240 sccm between 1420 and 950 cm$^{-1}$ with Gaussian/Lorentzian components (c) XRD pattern: 500 mTorr, 120$^\circ$C, 100 W, FRR 30 between angles 10$^\circ$ and 80$^\circ$. |
respectively. ULK F/C ratio is measured using XPS to be around 1.7, and the refractive index at 1.39 is closer to that of Teflon. C-V characteristics indicate the presence of inter-face trapped or bulk negative charges.

ACKNOWLEDGMENTS

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FIG. 12. (Color online): (a) XPS spectra of C 1s, (b) atomic concentration of species (A) C–C, C–Hn, (B) C–CF2, C–CF3, CF–C–CF, CF–C–CF2, (C) CF–CF2, CF–CF–CF, CF–CF–CF2, (D) –CF2–, CF–CF–CF2, –CF2–CF–, (E) CF–, (F) CF–CF and F/C ratio by XPS and EDS, (c) relative area of chemical bonds present in the C1s XPS spectra: 500 mTorr, 100 W, (A) FRR 25, 120 °C, TF 1040, (B) FRR 20, 160 °C, TF 840, and (C) FRR 12.5, 160 °C, TF 540.


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