Study on Metrology of ERU Tuning in TCP Reactor Using PVx2 Sensor Wafer

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Abstract* – The effect of the transformer-coupled capacitive tuning (TCCT) parameter on the etch rate uniformity (ERU) in a high density plasma etch chamber was studied by the following means: blanket wafer experiments; tests on patterned wafers with 20-nm half-pitch BEOL interconnect trenches, created by spacer defined double patterning; and PlasmaVolt^{TM} X2 (PVx2) sensor wafer experiments. Besides pure Ar and pure SF_6 chemistries, several typical process chemistries of poly-Si and SiO_2 etching were selected for study. It was shown that the ERU data (expressed as 3σ) were in good agreement for all the chemistries applied to both PVx2 and blanket SiO_2 with different TCCTs. The ERU of blanket poly-Si, however, did not generally correlate well with the PVx2 data. Only Ar sputtering and Cl_2/HBr–based processes showed a similar 3σ trend for both PVx2 and poly-Si. For the 20-nm half-pitch wafers, a study was performed on three separate etch steps with different chemistries, used for SiOC, BARC, and SiN etching. The critical dimension (CD) uniformity data was compared to the PVx2 results and demonstrated a good correlation in the first two cases. Based on these results, it was concluded that PVx2 is able to predict the behavior of the ion-assisted etch component in terms of uniformity, while spontaneous chemical reactions and/or ion-assisted polymer deposition could result in a substantial discrepancy between the actual ERU data and the PVx2 results. Finally, for materials that are typically etched using a dominant ion-assisted etch component, it was estimated that use of this PVx2-based method of ERU tuning may result in lot turn time savings of 80% when compared to single-use blanket wafer ERU tests.

I. INTRODUCTION

Uniformity control in plasma etch processes and process stability requirements are major challenges in high-volume production and they are becoming more aggressive for each new node. Understanding the reason for possible drifts as well as facilitating on-line data acquisition are becoming key elements for effective process optimization. It is known that the transformer coupled capacitive tuning (TCCT) parameter of the 2300® Versys® Kiyo3x chamber (Lam Research) allows changing the spatial plasma density distribution via an independent biasing of the segments of the TCP coil. Thus, TCCT was selected as a straightforward parameter that clearly influences the etch rate uniformity (ERU) distribution measured on blanket wafers and can be used to study the spatial portion of RF current passing through single detector areas of PlasmaVolt^{TM} X2 (PVx2), whose signal amplitude is linked to the magnitude of local plasma impedance [1]. This study has established a baseline from which a re-usable wafer-level metrology could be developed to greatly reduce the time needed for characterization and process optimization.

II. EXPERIMENTAL

The selected reactor, 2300® Versys® Kiyo3x (Lam Research) widely used for conductor etch and MEMs structure formation in silicon is shown in Fig.1. As mentioned above, the reactor is capable of changing the spatial (lateral is of interest) plasma density distribution via an independent biasing of several segments of the transformer coupled plasma (TCP) reactor's coil --- the effect of the TCCT parameter. Four discrete values of the TCCT setting were tested for each selected recipe, staying within the operational range of TCCT (from 0.1 to 1.5). In this operation, the higher TCCT setting corresponds to a larger fraction of power directed towards the center segment of the TCP coil. The corresponding recipes are listed below:

10mTorr Ar 121V/800W **(1)**
5mTorr $N_2/CH_2F_2/SF_6$/He 50V/625W **(2)**
10mTorr CF_4/CH_2F_2 100V/800W **(3)**
10mTorr HBr/Cl_2 150V/800W **(4)**
10mTorr SF_6 100V/800W **(5)**

The electrostatic chuck (ESC) temperature was kept at 60°C. The DC bias for the Ar-sputtering recipe was selected to provide an ion energy well above sputter-threshold level for SiO_2, which was estimated to be at around 50eV [2].

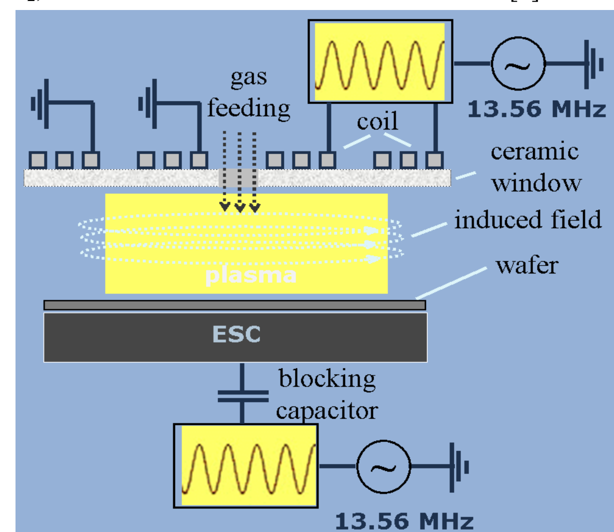

Fig.1. Operational principle of the TCP reactor: the top coil power source controls plasma density, while the bottom one controls ion energy.

The PVx2 sensor wafer has 14 capacitive detectors surface-mounted on the wafer. Each one is connected to an RF peak detection unit calibrated at 13.56 MHz. The detectors and circuitry are protected by a 100-µm thick polyimide layer providing isolation from the plasma. A threshold level of RF bias is required to enable measurements. A data collection frequency of 1 Hz was used for all experiments.

First part of the study was done with 300mm blanket wafers of two types: either with 600nm PE-CVD SiO_2 on Si or with 200nm poly-Si (low pressure CVD) on SiO_2/Si. They were treated with different recipes covering the four different TCCT values. Thickness measurements were completed using a KLA SCD-100 ellipsometer by means of a 14-points algorithm adapted to measure the thickness at the precise location of each PVx2 detector. The ERU data was extracted and converted into 3σ values to compare them with the data from the PVx2.

For the 20nm half-pitch interconnect trenches, experiments were performed for several critical steps. Process uniformity data was obtained through critical dimension (CD) measurements performed with a top-down eCD SEM at 25 points all over the wafer. Thus, CD uniformity (CDU) measurement was done after formation of APF masking material lines, which should have a uniform distribution of line widths (Fig.2a). Another CDU measurement step was inserted after the high-precision cut-off step of the SiN spacer (Fig.2b). The former measurements were done after SiOC removal, while the latter were performed after resist and BARC strip.

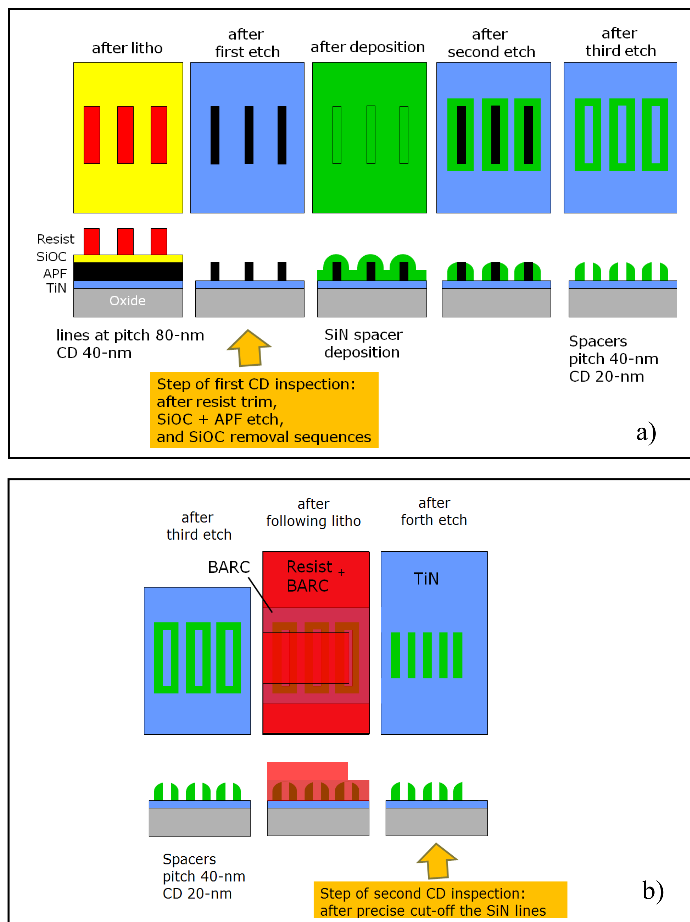

Fig. 2. Two CD inspection steps on patterned wafers: one after APF line patterning (a), and another one after spacer end cut-off (b).

III. RESULTS AND DISCUSSION

An example of experimental data obtained from PVx2 experiments is shown in Fig.3. Time slices for particular TCCT settings clearly show uniformity differences from one-another. The main question is whether the RF current non-uniformity represents the real situation in the plasma.

As discussed in [1], the measured value is proportional to the RF current coming from the bottom RF generator and passing through each single detector, which can be thought of as a measure of local plasma impedance. If we could assume an equal path length in the plasma for the RF current passing through each sensor, i.e. a straight line from the “source”, which is the detector, to the “drain”, which is a corresponding spot somewhere on the top of the reactor opposite to the detector, it would be possible to attribute the observed results only to the lateral non-uniformity in plasma. Of course, things are more complex than this “straight line” approximation. First, in the TCP reactor there are a few advantageous “drain” spots with a stronger degree of coupling between the TCP coil and the plasma. Second, using a 13.5MHz frequency under the typical high plasma density regimes of a TCP reactor there are some non-linear plasma effects appearing that have to be taken into account, for example, such as local conductivity differences manifesting in skin effect [3, 4]. Thus, the distribution shown in Fig. 3 is not only due to the non-uniform distribution of plasma species itself but also due to other effects influencing differently the RF path length for each detector.

Now, how can we interpret the result of relative RF current change as a consequence of process parameter variation, and interpret varying the TCCT in particular? Electrons are known

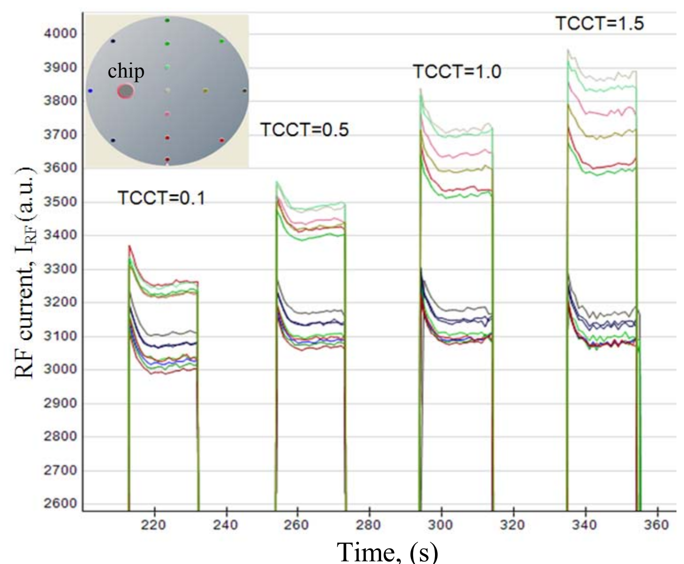

Fig. 3. Experimental data taken with PVx2 in Ar plasma, see recipe details (1); Inset represents the sensor wafer layout.

to be the carrier of RF current in plasma bulk, so one can consider the link between RF current and plasma density. An example of such an approach can be found in [5], where authors established a scaling law linking RF current to both electron density and temperature.

An additional effort is needed if we want to check/establish a correlation between the initially measured AC parameter (RF current) and real on-wafer results (ERU). The latter is essentially determined by such “DC” plasma parameters as ion energy or ion flux. So, to cover the gap between what we have and what we need, we have to rely on modeling. A good example can be found in [6], where authors expressed the average ion energy as a function of RF current:

$$\bar{E} \sim \frac{I_{rf}}{\omega \cdot P}$$

where P is the pressure and ω is the driving frequency.
An experimental validation was shown there for a frequency source of 13.5 MHz at the high pressure range (several hundred mTorr).

As a spot-check of which sorts of dependencies we have at low pressures, an Ar sputtering experiment was undertaken (see recipe details in (1)). Fig. 4 shows the uniformity map for PVx2 and an ERU map for blanket poly-Si and SiO_2 subjected to the Ar plasma at TCCT=0.5. In the Ar plasma the sputter etch rate depends on the ion energy or, more generally, on the energies and fluxes of ions. The good apparent correlation between the ERU and the RF current distribution measured in the TCP reactor (Fig. 4) suggested that it is useful to try to use PVx2 for the relative ERU assessment in the same reactor for different chemistries.

A. Blanket wafer experiments

There was a strong correlation between the SiO_2 data and the PVx2 read-outs for all chemistries studied (Fig. 5). For all chemistries except (4, 5), the ERU had the best result (TCCT = 0.1) when most of the power was applied to the outer segment of the TCP coil. Though the absolute values of 3σ differ, the trend for the SiO_2 ERU is nicely represented by PVx2 data. However, for poly-Si the correlation is not as nice (Fig. 5a). The settings for best ERU are shifted towards higher TCCT values and neither the trend nor the position of the extrema can be deduced from the sensor wafer data for the

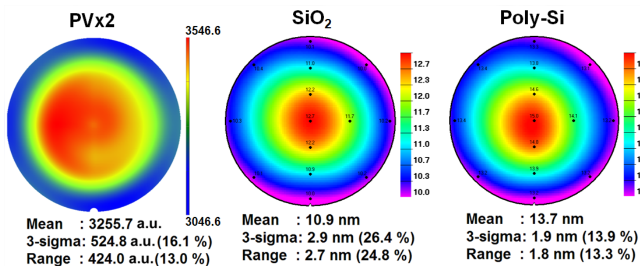

Fig. 4. Uniformity map forming under Ar plasma treatment (1) at TCCT = 0.5 and process time of 1 min

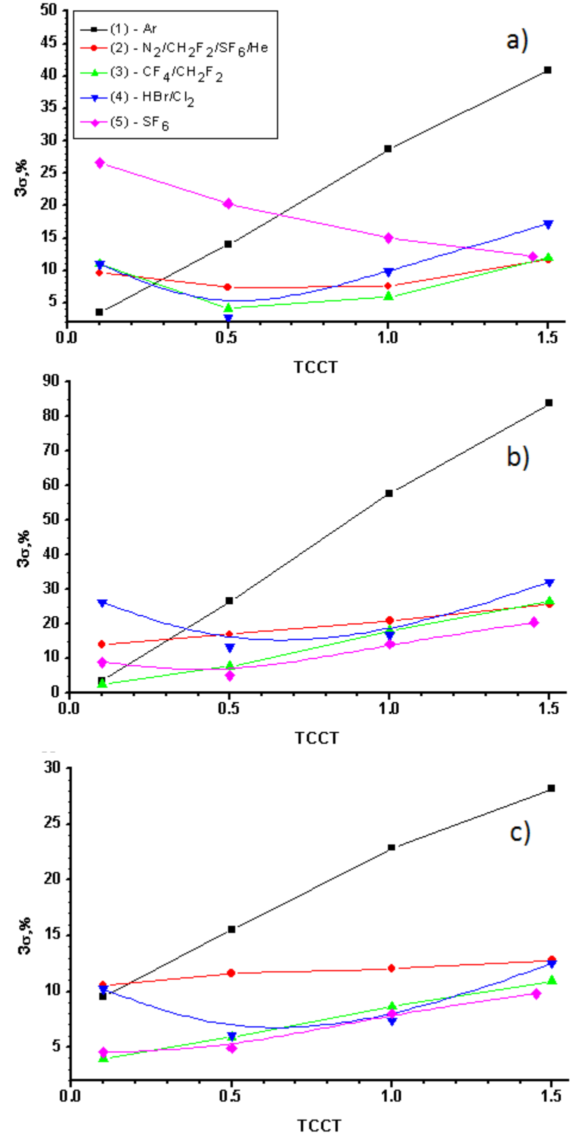

Fig. 5. ERU data for: (a) Blanket poly-Si and (b) Blanket SiO_2; and the uniformity data for PVx2 (c) --- with 5 recipe types: (1) through (5)

fluorine-based chemistries, which show a discrepancy, while HBr/Cl_2 or Ar-sputtering still show the same trend as the PVx2 data. It is well known that at room temperature, silicon etching with Cl_2/HBr plasmas requires ion assistance while in fluorine chemistries unassisted etching proceeds; in particular this is true for pure SF_6 plasmas. From the results for SiO_2 etching, which always requires ion assistance and has the best correlation with PVx2, results suggest that the PVx2 can be used for quick recipe tuning in terms of uniformity for processes that have a strong ion-assisted component.

The method is, however, likely to be less effective for other type of processes. Besides spontaneous chemical reaction there is an ion-assisted polymer formation [7] that may influence the results. It was shown that depending on the type of radicals in the plasma, the polymer deposition could be

more or less ion dependant, i.e. CF radicals are responsible for direct incorporation, while CF_2 radicals demonstrate an ion-assisted deposition behavior.

Thus, when the amount of polymerizing content in a complex recipe is well-tuned for good anisotropy, the wafer region subjected to an increased ion flux (due to spatial plasma non-uniformity) could perhaps in some cases switch to a stronger polymer build-up regime, preventing form etching. This might be important to take into account when trying to analyze the exact ERU extrema positions with respect to the TCCT in case of Si etching in fluorocarbon plasma.

B. Patterned 20-nm half-pitch trench wafers

Generally speaking, the ERU and the top-down SEM data of CDU are not transposable definitions and a direct correlation between these two data sets should not be expected. Meanwhile, an indirect correlation due to, for example, a lateral masking material erosion might be possible.

The SiOC etch recipe, applied to the patterned lot, was shown to have the best PVx2 uniformity at TCCT = 0.1 (green curve (3) Fig. 5c).

Fig. 6 shows both the snapshot SEM images taken at 25 locations all over the wafer (TCCT = 0.1 was used in the SiOC etching step) and the CDU data of APF lines measured at first inspection step. There was a clear trend of CDU improvement with smaller values of TCCT which correlated well with the PVx2 data (Fig. 6b).

Another situation is shown in Fig. 7. Here, the inspection was performed after high-precision cut-off step of the SiN spacers and the uniformity result of the patterning is presented in Fig. 7b for two sequential etch steps studied, namely, BARC opening and SiN patterning. The former utilized HBr/O_2 gas chemistries at 8mTorr, while the latter was done with a CH_3F/O_2 mixture at 40mTorr. The power settings were comparable in both cases.

As it is seen in Fig. 7b, there appears to be no correlation with PVx2 for SiN etching in CH_3F/O_2 plasma, while for the BARC etch step, such a correlation is present. Though by the bonding energy the SiN is more similar to Si than to SiO_2 (Si-Si ~325 kJ/mol, Si-N ~470 kJ/mol, Si-O ~799.6 kJ/mol [8]), the ions are required to proceed with SiN etching and the spontaneous chemical reaction rate with fluorine should stay extremely low even for PE-CVD type of material with some traces of hydrogen. This brings us to the point discussed at the beginning of the section: With CH_3F/O_2 chemistry we do have a good selectivity towards the masking material, so we cannot correlate the CDU with ERU (or with PVx2) and this is most likely the reason for the discrepancy.

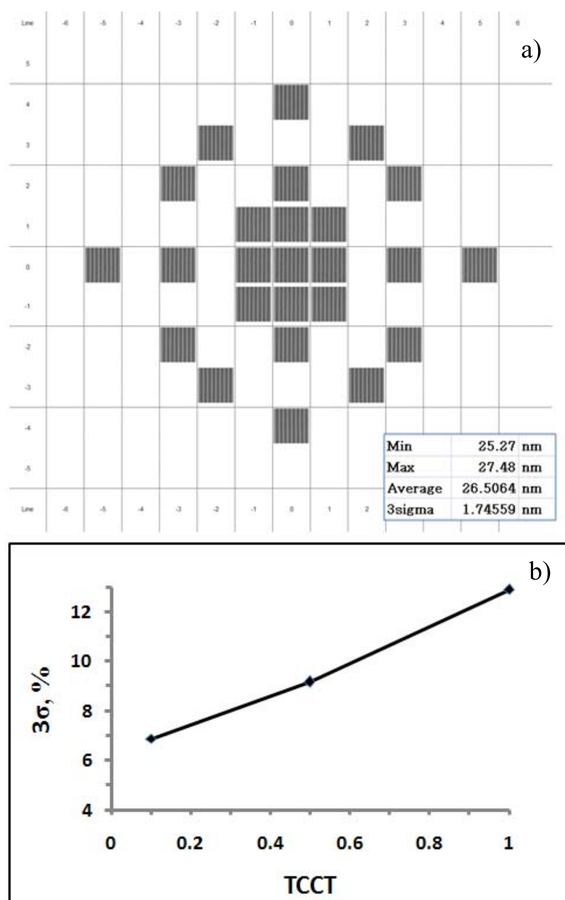

Fig. 6. (a) The measurement pattern with one of the best sets of CDU data obtained at the SiOC etching with TCCT=0.1; (b) CDU of APF lines as a function of TCCT (in SiOC etch step)

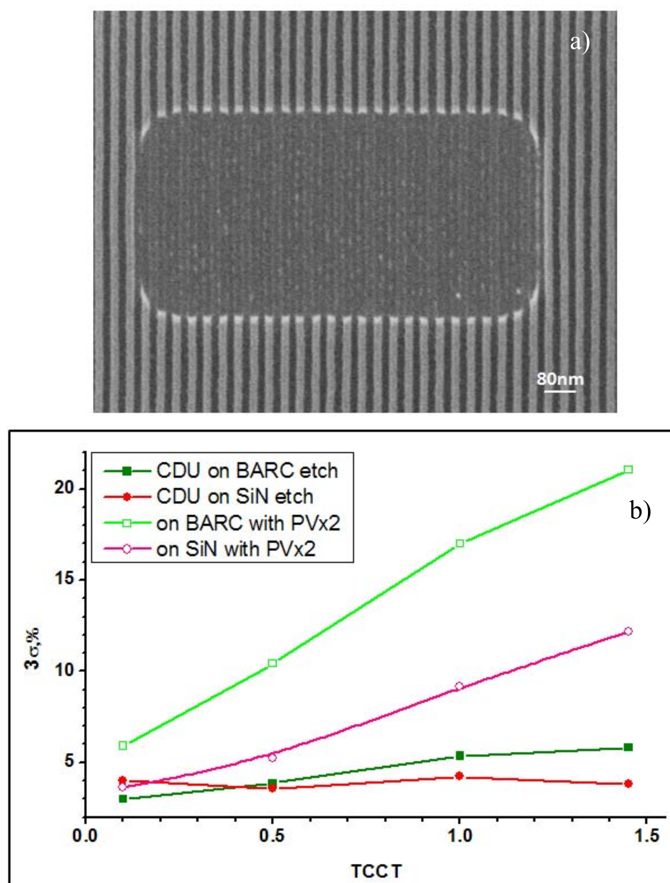

Fig. 7. (a) Top-down SEM image of the high-precision line cut-off window after full processing; (b) Uniformity data for several processes as a function of TCCT

IV. CONCLUSION

Data from the sensor wafer showed a good correlation with blanket SiO_2 ERU results for all of the etch chemistries tested, while there was no correlation with the ERU of blanket poly-Si wafers for fluorine-based chemistries tested. These observations suggest ion-assisted processes, for which uniformity trends in a TCP reactor may be predicted using a PVx2. The sensor is not capable of predicting purely chemical etching behavior and it could be challenging to interpret results for the substrates and processes where ion-assisted polymer build-up is likely. On the other hand, this discrepancy may be used to determine what is the dominant component or mechanism of a particular etching.

In the patterned 20-nm half-pitch lot, a good correlation of PVx2 and CDU data was found for the SiOC etch step in the first part of narrow APF lines patterning and for the BARC etch in the line cut-off step, while there appears to be no correlation for SiN patterning with a CH_3F/O_2 plasma at 40mTorr. The latter indicates the limitation of contrasting the ERU and top-down CDU data sets. Finally, in the TCP reactor, the PVx2 wafer can easily be used for a quick recipe tuning of processes like SiO_2 etching, where the ion-assisted component is by far the most dominant one. In appendix it is shown that lot-turn time savings of 80% or more can be achieved when compared to single-use blanket wafer ERU tests.

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APPENDIX

A. Time savings estimate for SiO_2 ERU optimization:

TC = 4, is the # of different TCCT values tested;
N = 6 x TC = 24, is the # of blanket test wafers used in one lot for the study (5 test wafers + 1 confirmation run per each chemistry);
LT = 6, is the # of lot turns for SiO_2 lot used in study; LT is counting irrespective of N and for blanket SiO_2 lot it is explained below:

1. ComposeLot,
2. Clean,
3. Dielectric Deposition,
4. Pre-Measurement,
5. Plasma etch,
6. Post-Measurement.

Meanwhile, for PVx2 the $LT_{PV} = 1$ since there is one operation only (and only one wafer used).

That is why: $[1 - (LT_{PV} / LT)] \times 100\ \% \approx 80\%$ TIME SAVINGS estimate in terms of lot turns irrespective of N. The number of blanket wafers that could be saved is N = 24.

Experiment completion times using a PlasmaVolt X2 system are typically less than 1 hour to study all different settings in separate steps of a single recipe (or in several recipes), while the lot turn of blanket wafers depends on N and on the queuing in process line, since several different steps are required to compose the lot and to fulfill the study.

REFERENCES

[1] A.P. Milenin, J.F. de Marneffe, H. Struyf, and W. Boullart, “In-situ Spatial Analysis of RF Voltage during Plasma Etching”, ECS Trans. 13 (8), 2008, pp. 17-22.
[2] Y. Yin and H.H. Sawin, “Surface roughening of silicon, thermal silicon dioxide, and low-k dielectric coral films in argon plasma”, J. Vac. Sci.Technol. A 26(1), 2008, pp. 151-160.
[3] V.A. Godyak, R.B. Piejak, and B.M. Alexandrovich, “Electrical characteristics and electron heating mechanism of an inductively coupled argon discharge”, Plasma Sources Sci.Technol. 3, 1994, pp. 169-176.
[4] J. A. Meyer and A. E. Wendt, “Measurements of electromagnetic fields in a planar radio-frequency inductively coupled plasma source”, J. Appl. Phys. 78 (l), 1995, pp. 90-96.
[5] M. J. Titus, C. C. Hsu, and D. B. Graves, “’SensArray’ voltage sensor analysis in an inductively coupled plasma” J. Vac. Sci. Technol. A 28(1), 2010, pp. 139-146.
[6] B.E. Thompson, K.D. Allen, A.D. Richards, and H.H. Sawin, “Ion bombardment energy distributions in radio-frequency glow-discharge systems”, J.App.Phys. 59(6), 1986, pp. 1890-1903.
[7] M. J. Sowa, M. E. Littau, V. Pohray, and J. L. Cecchia, “Fluorocarbon polymer deposition kinetics in a low-pressure, high-density, inductively coupled plasma reactor”, J. Vac. Sci. Technol. A 18(5), 2000, pp. 2122-2129.
[8] D.R. Lide, “Handbook of chemistry and physics”, 85th edition CRC Press LLC, 2004, pp. 9-54 --- 9-57.