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Stefan Decoster, Souvik Kundu, Frédéric Lazzarino, Stéphane Larivière, Martin O'Toole, Gayle Murdoch, Quoc Toan Le, Marleen van der Veen, Nancy Heylen, "Patterning of Ru metal lines at 18nm pitch," Proc. SPIE 12056, Advanced Etch Technology and Process Integration for Nanopatterning XI, 1205604 (25 May 2022); doi: 10.1117/12.2614267

Event: SPIE Advanced Lithography + Patterning, 2022, San Jose, California, United States

Patterning of Ru metal lines at 18 nm pitch

Stefan Decoster*[a], Souvik Kundu[a], Frédéric Lazzarino[a], Stéphane Larivière[a], Martin O'Toole[a], Gayle Murdoch[a], Toan Quoc Le[a], Marleen van der Veen[a] and Nancy Heylen[a]
[a]IMEC, Kapeldreef 75, 3001 Heverlee, Belgium

*stefan.decoster@imec.be

ABSTRACT

In this work, we present two different approaches to pattern Ru metal lines at a metal pitch of 18 nm, by making use of self-aligned double patterning (SADP) in combination with EUV lithography. The first and more conventional patterning approach is to define the 18 nm pitch gratings into a hard mask by means of SADP, which is consequently transferred into the Ru layer by means of direct metal etch. The second and more innovative approach consists of a combination of direct metal etch and damascene filling of Ru. This so-called mixed flow is a patterning-friendly approach which enables the integration of self-aligned cuts and vias. We will share the schematics as well as the results for 18 nm pitch Ru gratings on 300 mm Si wafers for both approaches. Finally, we will discuss and demonstrate the enablement of self-aligned cuts and vias for the mixed flow, which makes this patterning flow a promising alternative to standard damascene patterning for future interconnects at sub-20 nm metal pitches.

Keywords: back-end-of-line (BEOL), ruthenium, interconnects, direct metal etch, double patterning, SADP, damascene

1. INTRODUCTION

In the back end of line (BEOL), Cu-based damascene-style interconnects have been around for almost three decades in many consecutive technology nodes. As we are slowly progressing towards metal pitches of 20 nm and smaller in the BEOL interconnects, the resistance of Cu metal lines is increasing rapidly due to surface and grain boundary scattering.[1-2] Therefore, many research efforts are currently spent to find alternative metals to replace Cu at these small pitches, both for metal lines as well as for vias.[2-3] Some of the most-promising candidates (such as Ru, Mo), have a major patterning advantage over Cu, as they can be directly patterned by dry etch or so-called *direct metal etch* (DME). For DME, a blanket metal layer is deposited and later patterned, using a dedicated hard mask and directional etch, while damascene patterning consists of defining dielectric trenches which are later filled with metal and planarized. As a blanket metal layer is expected to reach a larger average metal grain size compared to metal filled in small trenches, DME has a possible advantage of lower resistance metal lines compared to the damascene approach. Furthermore, using direct metal etch also opens the possibility for exploring new integration concepts and scaling boosters, such as semi-damascene patterning[4,5], hybrid height metal lines, pillar vias and alternative patterning schemes for self-aligned blocks/cuts and vias, as will also be evidenced by the work presented here.

A very promising candidate material to replace Cu in future metal interconnects is ***ruthenium*** (Ru). Ru integration doesn't require a barrier layer, and patterning of Ru through DME has already been demonstrated down to pitches below 20 nm.[6-7] Moreover, due to the existence of RuO_4 as the volatile by-product, an O_2-based etch plasma is used which results in good hard mask selectivity toward many typical hard mask materials such as SiO_2, Si_3N_4, TiN and others. A major challenge for patterning Ru metal lines at such small pitches, is to avoid bridges in the metal trenches during patterning. This is not only valid for metal etch but is applicable for most materials, although it has been indicated as a particular challenge for Ru metal etch.[7]

To enable sub-20 nm pitch gratings, single print EUV lithography needs to be combined with a double patterning technique such as litho-etch-litho-etch (LELE) or ***self-aligned double patterning*** (SADP). While LELE patterning adds an extra overlay constraint between both litho patterns, the self-alignment principle of SADP is considered a more

Advanced Etch Technology and Process Integration for Nanopatterning XI, edited by
Julie Bannister, Nihar Mohanty, Proc. of SPIE Vol. 12056, 1205604

promising approach with respect to edge placement error (EPE) budget. Therefore, the rest of this study is making use of a combination of EUV lithography with SADP.

SADP patterning, which doubles the number of printed lines, can be done in two different ways, as is presented in Fig. 1. In both ways, first a mandrel or core is being defined, followed by a conformal spacer deposition and spacer etch back step, which is schematically represented in the first three cartoons in Fig. 1. The most straightforward continuation of the SADP flow is to remove the mandrel material and use the remaining spacers as the mask to pattern the next layer, as is shown in Fig. 1a. The second and technically more challenging approach, is to keep the mandrel material in place, fill and planarize the *gaps*, and finally remove the spacers. In this way, which is shown in Fig. 1b, the original mandrel and the filled gap become the mask to pattern the layer below.

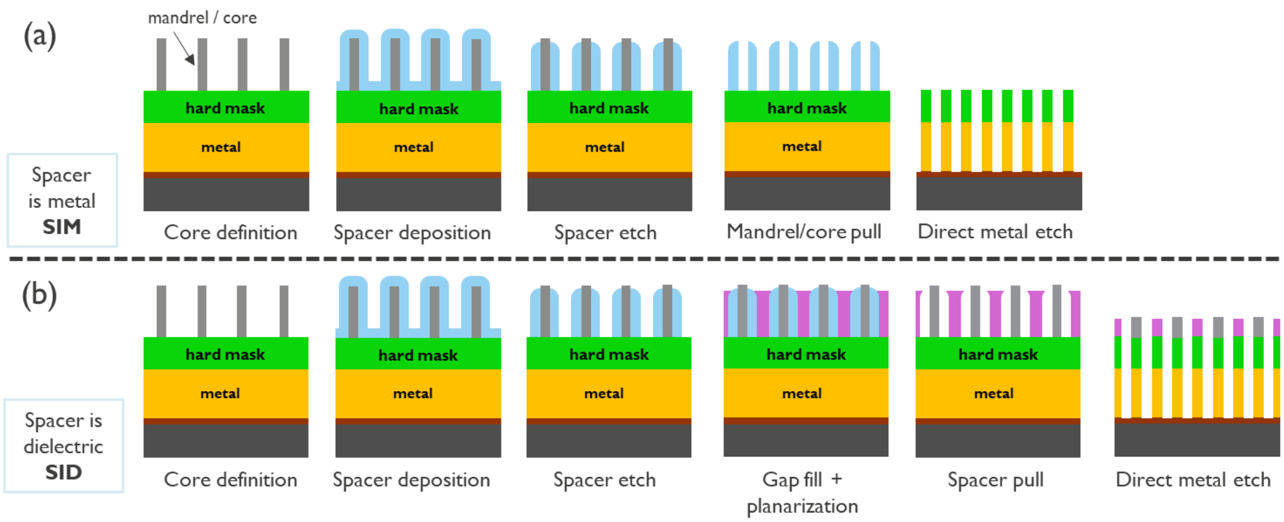

Figure 1. Two different SADP patterning approaches to double the number of originally patterned lines and transferring them into a metal layer below by direct metal etch. (a) The 'spacer-is-metal' (SIM) approach in which the mandrel is removed and the spacer lines are the mask to pattern the metal layer below. (b) The 'spacer-is-dielectric' (SID) approach in which the mandrel is not removed, but instead all remaining 'gaps' are filled and planarized, after which the spacers are removed, and the mandrel and gap are the mask to transfer the patterns in the metal layer below.

When applying this SADP patterning to the back-end-of-line (BEOL) interconnect metal layers, these approaches result in a so-called *spacer-is-metal* (**SIM**) approach (Fig. 1[a]) or in a *spacer-is-dielectric* (**SID**) approach (Fig. 1[b]), respectively. For the SIM approach, the spacers are defining the metal, which means that the critical dimension (CD) of the metal lines is defined by the spacer deposition thickness and therefore fixed, while the CD of the dielectric material in between the metal lines is variable and defined by design. On the other hand, in the SID approach the metal lines are defined by the mandrel and the gap which enables a variation in the width of the metal lines, while the dielectric space in between the metal lines is fixed by the spacer deposition thickness. The freedom to have a variable metal line CD is in general more favorable for design, and the SID approach is the most likely patterning option for the future interconnects that make use of DME patterning.

To be able to make the necessary interconnects, the gratings need to be locally **cut** and connected to upper- or lower-level metal layers by means of **vias**. As we are targeting very small features (< 20 nm pitch), the relative placement of the cuts and vias with respect to the gratings (which could be impacted by, amongst others, overlay, CD uniformity, line edge roughness) becomes very important. A convenient approach to increase this so-called EPE budget in the direction perpendicular to the direction of the gratings is to make use of the self-aligned cut (SAC) and self-aligned via (SAV) concepts. Self-aligned cuts or vias can be defined in different ways. In the current study, we refer to being self-aligned not only to the trenches around the (metal) line, but even to the neighboring (metal) line. This is schematically explained in Fig. 2, where the cut and via mask are drawn in Fig. 2[a], and the result after self-aligned patterning in Fig. 2[b]. The naming convention used in this study is that SAC A cuts the A line, while being selective to the B line, and vice versa. In a similar way, SAV A connects to the A line while the connection to the B line is not allowed, and vice versa.

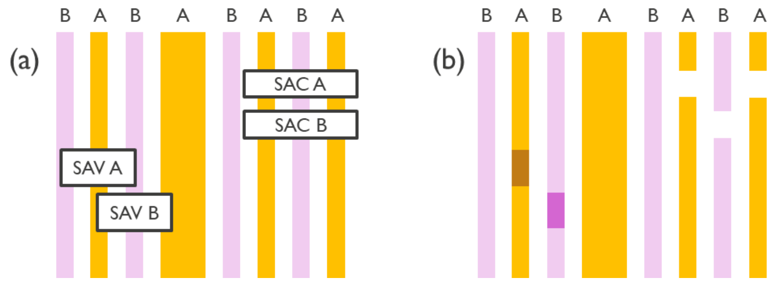

Figure 2. A schematic representation of the self-aligned via (SAV) and self-aligned cut (SAC) concepts used in this study (a) before and (b) after transferring into the A/B gratings. In both cases, the cut/via is defined in a selective way, not only toward the neighboring trenches but also toward the neighboring line.

This kind of self-alignment can be reached when neighboring (A/B) lines have a different origin (as presented by different colors in Fig. 2) or if one of the two types of lines is not yet present and only defined later in the flow. When patterning metal lines with DME by means of SADP in the SID approach, neighboring lines are alternately defined by the mandrel and by the gap, hence have a different origin and can be used to define these type of self-aligned patterning boosters. In the SIM approach, all metal lines are defined by the same spacer material, and therefore such self-aligned patterning boosters are not possible to integrate easily.

In this work, we will present the results for two different approaches for patterning Ru metal lines at a metal pitch of 18 nm, by making use of direct metal etch and a combination of EUV lithography with SADP. The standard damascene option in which dielectric trenches are defined, filled with Ru and planarized by chemical mechanical polishing will not be discussed here. The first approach is to pattern the gratings, including the cuts, into the hard mask and then transfer all patterns together in Ru. This means that the direct metal etch happens after the double patterning and therefore at the smallest possible pitch. The experimental results for this patterning approach, by using the SIM scheme (see Fig. 1[a]) are presented in **section 3**. Due to the use of SIM, there is no possibility to include SACs or SAVs in this patterning flow. A second and more innovative approach to end up with 18 nm pitch Ru gratings is to combine direct metal etch with damascene patterning, which we will refer to as the 'mixed' process flow in the remainder of this manuscript. This is an SID approach, and the schematic process flow, together with the experimental results are shared in **section 4**. As this mixed DME-damascene patterning flow uses the SID approach, the integration of two SACs and two SAVs can be enabled. The schematic representation as well as the experimental validation of the self-aligned cuts and vias in the mixed flow will be shared in **section 5**.

2. EXPERIMENTAL

All the experimental results shared in this study have been achieved on 300 mm Si full wafers. Physical vapor deposition (PVD) has been used to deposit Ru on top of SiO_2. A 5 nm TaN layer was used before the Ru deposition, mainly for adhesion purposes. SiN has been deposited on top of the Ru by plasma-enhanced chemical vapor deposition, which was used as the hard mask for Ru. Also here, a 1 nm TiN layer was used to promote the adhesion of the SiN on top of the Ru metal layer.

For the results shared in Section 3, the SADP patterning was done at the hard mask level, making use of an amorphous Si mandrel and SiO_2 spacers deposited by atomic layer deposition (ALD). As will be shown in section 4, we have filled small gaps with Ru by first using chemical vapor deposition (CVD), followed by a physical vapor deposition (PVD) overburden step. Before CVD deposition, a thin TiOx liner has been deposited for nucleation and adhesion reasons. Finally, the excess of Ru has been removed and the wafer has been planarized by chemical mechanical polishing (CMP).

The morphological analysis of the different processing steps has been done by cross-sectional and top-down scanning electron microscopy (SEM) and cross-sectional transmission electron microscopy (TEM) complemented with elemental dispersive x-ray analysis (EDX).

3. PATTERNING APPROACH 1: DIRECT METAL ETCH (WITH SIM)

One of the most straightforward ways to pattern 18 nm pitch Ru gratings is by using SADP in the SIM mode at the hard mask, and afterwards transferring the hard mask into the Ru metal layer. This approach is schematically represented in Fig. 1[a] and has been used to investigate the direct metal etching behavior of Ru at 18 nm metal pitch. In this section, we present the current status and the key findings of 18 nm pitch Ru gratings, patterned by DME.

In Fig. 3[a], a cross-sectional TEM image and a top down SEM image are shown for the starting condition before Ru direct metal etch, i.e. after SiN hard mask patterning. This is the results of transferring the SADP patterning into the SiN hard mask, without any noticeable line bridging or bending of the SiN gratings. This hard mask has then been transferred in a 20 nm thick Ru layer by direct metal etch, as shown in Fig. 3[b]. The profile of the Ru is close to 90° and the CD of the metal lines is ~10 nm. The hard mask has been barely consumed, indicating a very good selectivity of the O_2-based etch plasma to the SiN hard mask during Ru etch. As can be seen from the top down SEM image, some metal bridges occur, and this is currently one of the major challenges for patterning Ru at these small dimensions, as indicated in earlier reports.[7]

One of the major advantages of direct metal etch patterning is the possibility to define taller aspect ratio (AR) metal lines, compared to damascene patterning, where the lower mechanical strength of the low-k (porous) dielectric more easily causes line bending or even pattern collapse. Thanks to the sufficient hard mask selectivity, we have demonstrated 18 nm pitch Ru lines with an AR up to 3, as shown in Figs. 3[c] and [d] for a Ru thickness of 25 and 30 nm respectively. Based on the remaining hard mask after AR 3 patterning (Fig. 3[d]), it should be possible to even further increase the aspect ratio with the applied etch process.

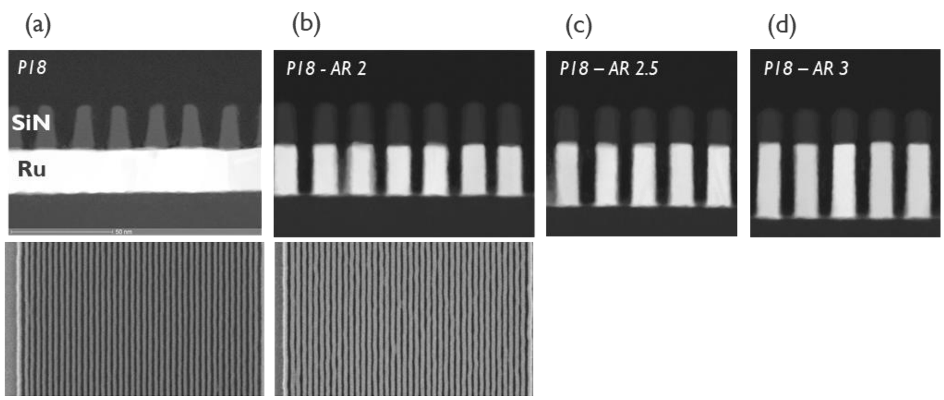

Figure 3. Cross-sectional TEM (top) and top-down SEM (bottom) images of 18 nm pitch gratings after (a) SiN hard mask patterning and after Ru direct metal etch for aspect ratio (b) 2, (c) 2.5 and (d) 3.

All results presented in this manuscript have been obtained on 300 mm full wafers, and the uniformity across the wafer is demonstrated in Fig. 4. The variation of the amount of hard mask remaining on the wafer is limited to 1.5 nm, indicating a mature full wafer hard mask and Ru etch process. The variation in pitch-walking that can be noticed between the center and the edge of the wafer, is related to the CD variation of the mandrel definition at the start of the SADP process, and is not directly related to the Ru etch itself.

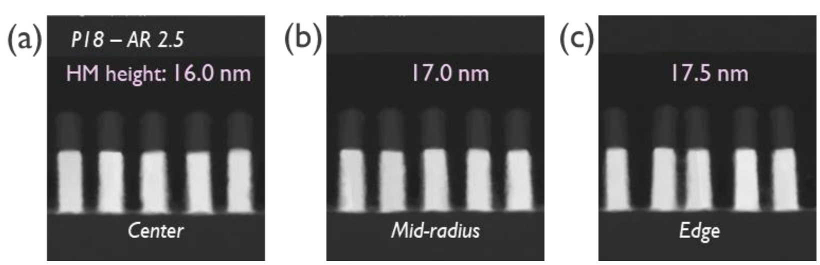

Figure 4. Cross-sectional TEM images of 18 nm pitch Ru gratings with an aspect ratio of 2.5, for (a) the center, (b) the mid-radius and (c) the edge of a 300 mm full wafer. The remaining hard mask height for the three images is indicated on the images.

An elemental analysis of the patterned Ru lines is shown in Fig. 5 for (a) Ru, (b) O, (c) N and (d) Si. From these images, it is clear that the SiN hard mask is oxidized, as can be expected after using an O_2-based plasma to pattern Ru and from the natural oxidation of SiN when exposed to atmosphere. More interestingly, however, is the absence of a native oxide on the sidewalls of the Ru metal lines (Fig. 5[b]). This is another major advantage of using Ru over other metals that do have a natural oxide formation after patterning, such as Mo or W.

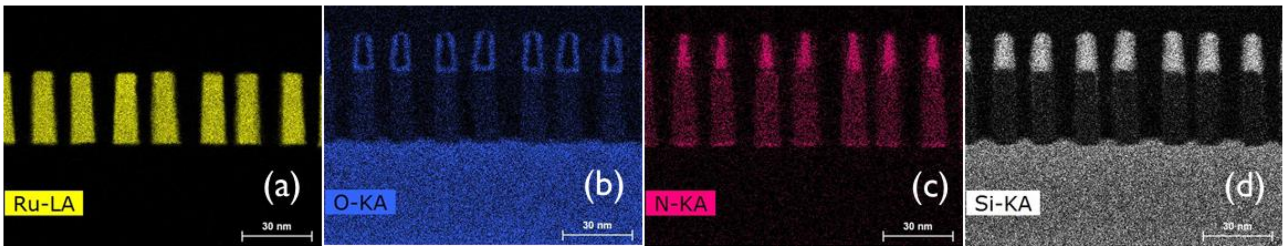

Figure 5. Elemental mapping of 18 nm pitch Ru gratings for (a) Ru, (b) O, (c) N and (d) Si by means of EDX from a cross-sectional TEM image.

In conclusion, we have demonstrated the feasibility to pattern 18 nm pitch Ru metal lines by direct metal etch with a straight profile up to aspect ratio 3, with good within-wafer uniformity and without a metal oxide layer on the sidewalls. All of these results are very promising and make DME of Ru a valid candidate to replace the standard damascene-style Cu in future interconnects at the smallest pitches.

4. PATTERNING APPROACH 2: MIXED FLOW OF DME AND DAMASCENE (SID)

4.1 Process flow

As demonstrated in the previous section, it is possible to pattern small pitch metal lines by first defining the SADP patterns (with eventually also some cuts) and then transfer the patterns by direct metal etch with the SIM approach in Ru. A major concern and technical challenge is the final patterning of the metal lines at the smallest pitches, which could potentially lead to metal bridging. Moreover, as explained before, self-aligned cuts or vias will not be possible using this patterning scheme.

To find a solution for both of these challenges, we have defined an alternative patterning approach, which combines direct metal etch and damascene patterning, and is therefore denoted as '*a mixed DME-damascene*' patterning scheme. A schematic representation of this process flow is shown in Figs. 6 [a-f]. First, the EUV-defined patterns are transferred into a sacrificial patterning layer, which is used to trim the patterned lines to the final target CD (Fig. 6[a]). In the next step (Fig. 6[b]), these patterns are transferred to the bottom metal layer by direct metal etch, and the resulting metal lines will be denoted as metal A lines. It needs to be emphasized that the direct metal etch step is now not happening anymore at the final pitch (18 nm) but at the much more relaxed litho pitch of 36 nm. Obviously, this will be a major improvement with respect to the metal bridging that has been observed when patterning Ru at 18 nm pitch, as presented in section 3.

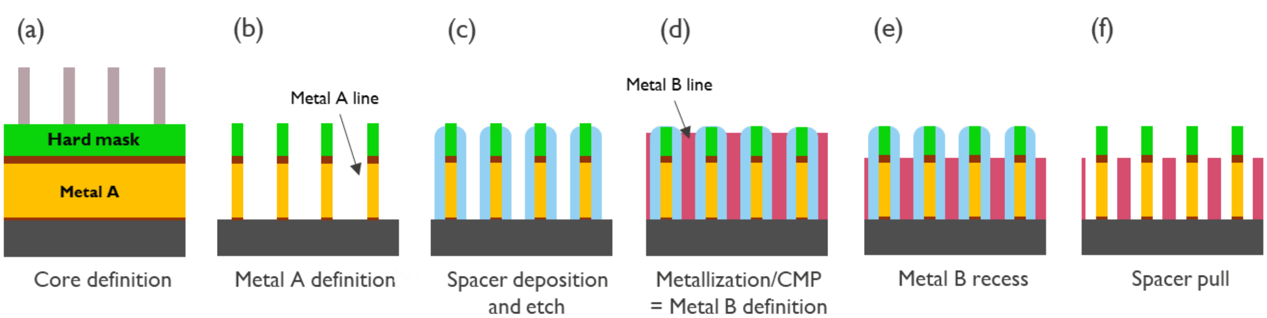

Figure 6. Schematic process flow of the mixed DME-damascene flow to make metal gratings by combining direct metal etch (metal line A) and damascene patterning (metal line B). (a) The mandrel is defined in a sacrificial patterning layer and (b) transferred into the metal layer by DME, followed by (c) spacer deposition and spacer etch. (d) The gaps are then filled

with metal and planarized, and (e) recessed back to have the same metal height as the metal A lines. Finally, (f) the spacers are pulled to continue the process flow with low-k gapfill or air gap formation.

After the definition of the metal A lines, a conformal spacer is deposited and etched back, as shown in Fig. 6[c]. Next (see Fig. 6[d]), the metal B lines are defined by filling and planarizing the remaining gaps in between the spacers with metal B. As both metal lines now have a different height, the metal B lines should be recessed to the level of the metal A lines, as shown in Fig. 6[e]. At this stage, we have defined metal lines after SADP patterning, by combining a direct metal etch approach for lines A, and a damascene approach for lines B. Due to the presence of the spacers around the metal A lines, the risk of metal line bridging (between A and B) is avoided. The flow can be further improved by removing the spacers (as shown in Fig. 6[f]) so they can eventually be replaced by a low-k material or by airgaps, to significantly reduce the capacitance between neighboring metal lines.

This *mixed flow* enables the use of two different metals A and B, or the same metal. A requirement for metal A is that it needs to be patternable through direct metal etch, while metal B does not have this restriction, in theory. However, as will be shown later, if a self-aligned cut of metal B is required, metal B also needs to be etchable through DME. Although DME is possible on other metals as well (e.g. Mo, W), we have defined this patterning scheme with Ru in mind, both for metal A and metal B. All experimental results shared in the remainder of this manuscript have been achieved with Ru as metal A and metal B.

4.2 Experimental results

As shown in Fig. 7, we have demonstrated the feasibility to pattern 18 nm pitch gratings of Ru, using the mixed DME-damascene flow concept. Cross-sectional TEM images are shown after direct metal etch patterning of the Ru A lines in Fig. 7[a]. The Ru metal lines have a straight profile, sufficient hard mask remaining on top and are very well separated, as can be expected from patterning thin lines (~12 nm) in a wider pitch (36 nm). Next, ALD SiO_2 has been used to define the conformal spacers on top of the Ru ‘mandrels’, after which the etch back of the spacers is performed (see Fig. 7[b]). The remaining gaps are then filled with CVD Ru and planarized by CMP. The final result of 18 nm Ru gratings without any risk of metal line bridging, is shown in Fig. 7[c], which demonstrates the feasibility of this mixed DME-damascene concept flow.

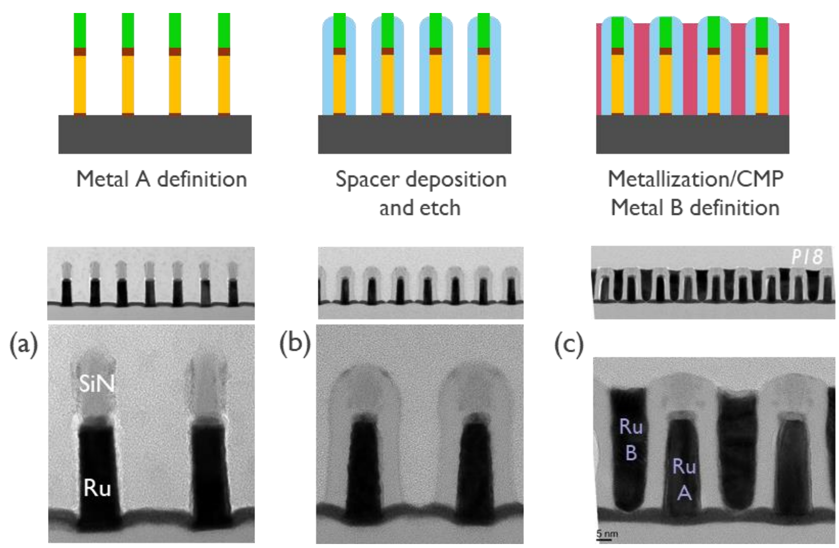

Figure 7. Schematic representation and cross-sectional TEM images after (a) metal A definition by direct metal etch of Ru, (b) ALD SiO_2 spacer deposition and spacer etch and (c) metal B definition by metallizing the trenches with Ru and planarization by chemical mechanical polishing.

Next, the Ru B lines need to be recessed to the level of the A lines, as schematically presented in Fig 6[e]. Therefore, recess tests were performed on the same type of structures, although at slightly larger pitch (21 nm). The results, as shown in Fig. 8, indicate that this recess process can be controlled well and has good selectivity towards the other materials present in the stack.

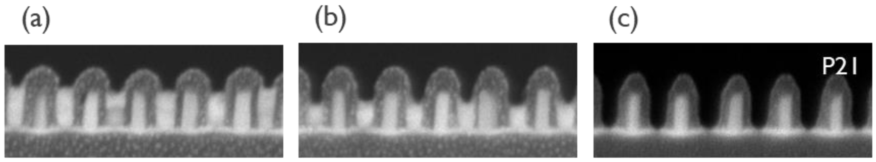

Figure 8. Cross-sectional SEM images after recessing metal B lines with different recess times: (a) 1×, (b) 2× and (c) 3×.

Finally, we have also demonstrated the feasibility to remove the oxide spacers without affecting the Ru lines (see Fig. 9). By using a wet dHF treatment, we have been able to fully remove the oxide spacers, selectively to the SiN hard mask on top of the metal A lines, as well as to the Ru metal lines themselves. Moreover, despite the non-optimal profile of the metal B lines (with a larger CD at the top compared to the bottom), no line bending or pattern collapse has been observed.

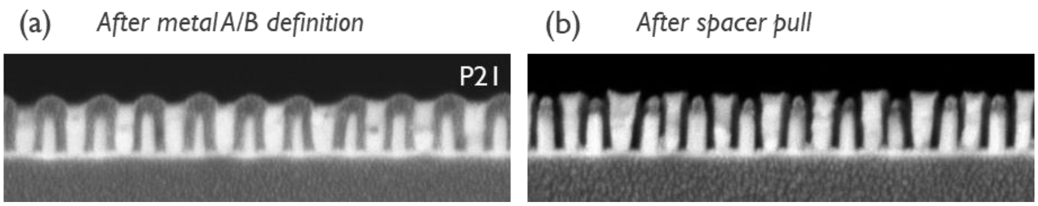

Figure 9. Cross-sectional SEM images of 21 nm pitch Ru gratings defined by the mixed DME-damascene flow, (a) before and (b) after oxide spacer removal by means of dHF.

From these results, we can conclude that there are no patterning-related showstoppers to define 18 nm pitch Ru gratings by means of this mixed flow, in which we define metal A lines through direct metal etch and metal B lines through damascene patterning. As we will see in the next section, this mixed flow also has the potential to integrate self-aligned cuts and self-aligned vias.

5. INTEGRATING SELF-ALIGNED CUTS AND SELF-ALIGNED VIAS IN THE MIXED FLOW

As has been explained earlier and as is shown in Fig. 2, the self-aligned cuts are intended to cut an ‘A’ line selectively to a ‘B’ line and vice versa, while the self-aligned vias are supposed to connect to a metal ‘A’ line while not connecting to a ‘B’ line and vice versa. In this section, we will demonstrate the feasibility of integrating both SAVs and SACs with the mixed flow concept. The schematic representation of the mixed DME-damascene patterning flow, as shown in Fig. 6, is now extended with the integration of both SAVs and SACs, as shown in Fig. 10. Each of the four patterning boosters (SAC A, SAV B, SAC B and SAV A) will be separately discussed in the following subsections, in order of appearance in the process flow.

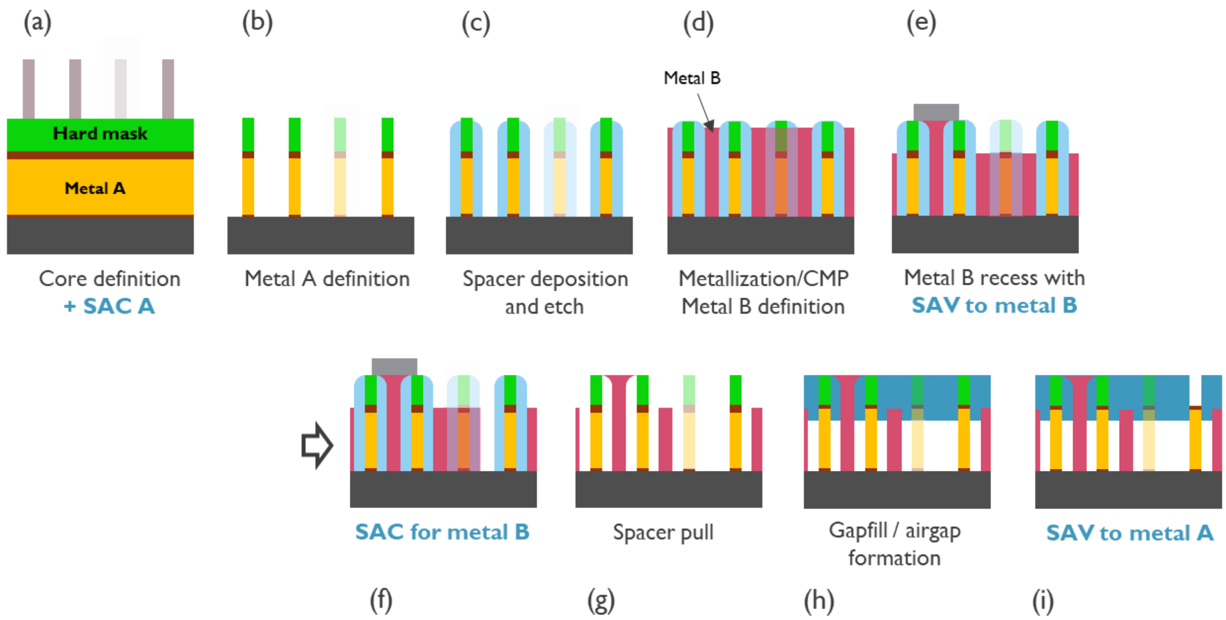

Figure 10. Schematic process flow of the mixed DME-damascene flow, including the self-aligned cuts of the metal A (SAC A) and metal B (SAC B) lines and the self-aligned vias to the metal A (SAV A) and metal B (SAV B) lines.

5.1 Self-aligned cut to metal A (SAC A)

The self-aligned cut of the metal A lines is done during the patterning of the hard mask, as shown in Fig. 10 [a]. Through the definition of a dedicated cut mask, the patterned lines can be cut locally. This process is selective to the metal B lines, as they have not yet been defined. Therefore, a cut of the metal A lines can never cut a metal B line. This SAC A can be done both at the hard mask level or after direct metal etch of the metal A lines, i.e., after the step shown in Fig. 10 [b]. Experimental validation of the SAC A (at hard mask level) has been done and is shown in Fig. 11. Top-down SEM images after metal A patterning in Ru are shown for an area without cuts and with cuts in Figs. 11 [b] and [c], respectively.

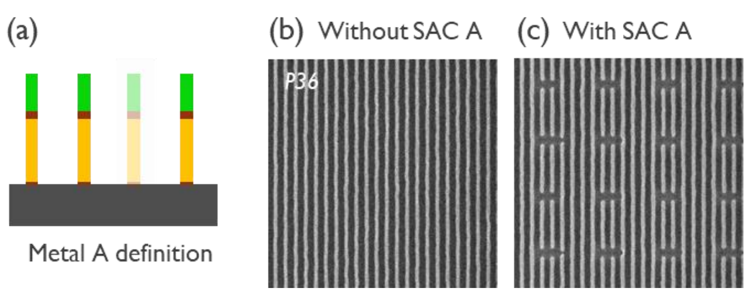

Figure 11. (a) Schematic representation and (b-c) experimental validation of the self-aligned cut of the metal A lines, for an area (b) without cuts and (a) with cuts.

5.2 Self-aligned via to metal B (SAV B)

The definition of the self-aligned via to the metal B lines happens immediately after the damascene patterning of the metal B lines, as shown in Fig. 10 [e]. Instead of recessing all the metal B lines to the level of the metal A lines, as was originally shown in Fig. 6 [e], we can define self-aligned vias by recessing the metal B lines everywhere except at the locations of the vias. This is done by using a tone-inverted version of a regular via mask, and then recessing the metal B lines while the via locations are protected by a hard mask.

A top-down SEM image after recessing the metal B lines with a via mask, is shown in Fig. 12 [b], in which the white elongated features are the areas protected by the via mask. A cross-sectional TEM image through these elongated via bars, as indicated by the cleaving direction on Fig. 12 [b], is presented in Fig. 12 [c]. From this TEM image, the recessed area and non-recessed or via-defined areas can be clearly distinguished. In those non-recessed areas, there are so-called *standing vias* present that only make connections to the metal B lines (SAV B), without making any connection (i.e. being selective) to the metal A lines.

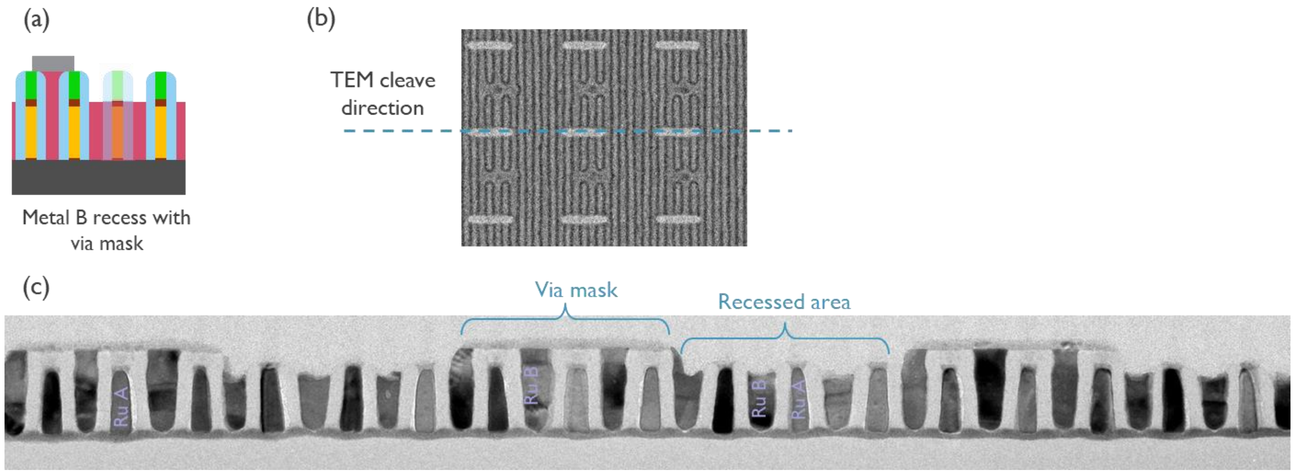

Figure 12. (a) Schematic representation of the self-aligned via to the metal B Ru lines. (b) Top-down SEM image and (c) cross-sectional TEM image of the experimental validation of the self-aligned via to the metal B lines, at the location indicated in panel (b).

5.3 Self-aligned cut to metal B (SAC B)

After defining the self-aligned vias to the metal B lines, the metal B lines can be cut selectively to the metal A lines (SAC B), as shown schematically in Fig. 10 [f]. By using a dedicated cut B mask, the metal B lines can be selectively cut if there is sufficient etch selectivity between metal B and all the other materials present in the stack. In the case of using Ru for metal A and metal B lines, SiN as the hard mask for the metal A lines and oxide spacers, etch selectivity should be easily achieved. As the metal A lines are still protected by the SiN hard mask, cutting the metal B Ru lines can be done without cutting the metal A lines. This patterning booster has not been experimentally validated in this study, but we do not foresee any showstoppers at this patterning step.

5.4 Self-aligned via to metal A (SAV A)

The fourth and final patterning booster is the self-aligned via connection to the metal A lines (SAV A), as schematically represented in Fig. 10 [i]. A self-aligned via can be created by etching the SiN hard mask on top of the metal A lines selectively to the surrounding dielectric material. The vias patterned in this way, can only make a connection to the metal A lines without being able to connect to the metal B lines, as the latter don't have any SiN hard mask on top. The experimental validation of this SAV A has been done on 18 nm pitch Ru gratings defined by a DME-only approach in SIM mode, as shown in Fig. 13.

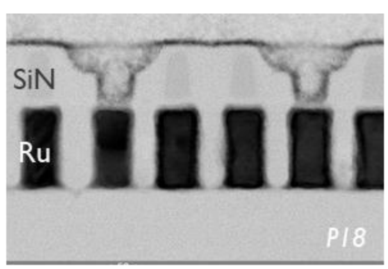

Figure 13. Cross-sectional TEM image of 18 nm pitch Ru lines with a SiN hard mask, and a self-aligned via patterned on top of the Ru lines. The self-alignment has been achieved by etching the SiN hard mask selectively to the surrounding oxide. This demonstration has been done on Ru gratings defined by a DME-only patterning process.

Based on the results from the previous subsections, we can conclude that we have demonstrated the feasibility of integrating two SACs and two SAVs in this innovative patterning flow that makes use of a combination of direct metal etch and damascene patterning to create tight pitch metal lines.

CONCLUSIONS

In conclusion, we have discussed different options to pattern 18 nm pitch Ru lines, both by using direct metal etch and by using a combination of DME and damascene. Results have been shared for both the DME-only and the DME-damascene mixed flow approach, in which aspect ratio 3 Ru metal lines were demonstrated at 18 nm pitch for both approaches. Moreover, we have demonstrated the feasibility of integrating SACs and SAVs in the mixed flow, which makes this flow a promising alternative compared to a Ru DME-only approach to replace standard Cu damascene patterning in future interconnects.

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