

Global I/O

Memory Semis & Semiscap

4F² DRAM adoption pulled in: Implications

Equities

Global
Semiconductors

Transition to 4F² VCAT DRAM could start in 2028

Based on industry checks, expert calls as well as reflecting recent commentary from semiscap equipment vendors, we believe all key DRAM vendors are assessing, and for some, pulling in, the adoption of 4F² vertical channel access transistor (VCAT) for DRAM chip design and process technology. Initial transition to 4F² should allow for a 'one-time' reduction in DRAM cell size (i.e. density increase) and offer performance improvement. We believe Samsung is strongly considering mass production adoption of 4F² to be pulled in to 2028 for 0a nm, with 1d nm the last 6F² node. SK Hynix may follow suit with 0a nm or wait til 0b nm, and Micron potentially after 1 epsilon (1e nm) at 0a nm. Either way, the 4F² train has left the station. As a follow-up to our initial 3D DRAM report ([link](#)), we assess in this note the key challenges and opportunities ahead that the transition to 4F² will present for both DRAM players as well as the ecosystem (semiscap equipment, semis materials).

Samsung likely first mover to 4F² DRAM, and why it matters

We believe Samsung will be first to adopt 4F² starting from 0a nm. We expect Samsung to prep 0a nm 4F² samples by 2H27 followed by mass production potentially starting in 2H28. This is in-line with recent commentary from wafer fab equipment vendors indicating visibility on initial 4F² equipments coming through for late-2027/early-2028, marking a pull-in vs. our prior expectations of late-2028/2029. This is we believe especially important for Samsung as the VCAT could help boost performance whilst the capacitor may benefit from a relaxation in design rule, hence reducing the aspect ratio. Having had a capacitor structure relatively tall and thin has, we believe, contributed to some of the performance and yields challenges for HBM. Hence, 4F² could actually contribute to Samsung moving ahead in DRAM technology.

Incremental growth avenue for semis equipment and material vendors

We believe the transition to 4F² DRAM will offer incremental opportunities for both semiscap equipment as well as semis materials. For semiscap, key segments to benefit include selective epitaxial growth, atomic layer deposition, rapid thermal processing, high aspect ratio etching as well as potentially hybrid bonding tools. Litho intensity may be diluted for the initial 4F² transition but that said, after a one-time relax in design rules, we believe litho shrink and eventually high NA EUV will be necessary for subsequent nodes. Semis materials segments benefiting include moly and ruthenium.

Stock implications

We would outline key supply chain beneficiaries within Semiscap: Applied Materials, Tokyo Electron, Lam Research, ASMI and Eugene Tech (all Buy-rated; TEL Key Call). Within semis materials, we would outline Merck, Air Liquide, Hansol Chem (all Buy-rated), whilst Entegris (Neutral) also has exposure. We continue to prefer SK Hynix (Key Call Buy) ahead of Samsung (Buy), but longer term, 4F² could play more in Samsung's favour.

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DRAM process tech at crossroads, again

DRAM 101 - A Short Recap

Under the current DRAM architecture/technology, each DRAM cell is comprised of one capacitor – which receives the charge/discharge for "0s" and "1s" – and one transistor – which admits/discharges the current into the capacitor. Each DRAM cell is also connected to a word line (control gate for cell access transistors) and bit line (data pathway) which allows the DRAM cell to perform both 'Read' and 'Write' operations (see Figure 1, page 3).

One DRAM cell is equal to 1 bit, and the respective cell area is defined as nF^2 , where n refers to the cell design and F refers to the smallest feature size of a given process technology (half pitch - smallest distance between two gates). The design of current mainstream DRAM adopts a $6F^2$ 'cell to area' ratio meaning that the area of one DRAM cell/bit is equivalent to six times the square of the half pitch (2F pitch for word lines x 3F pitch for bit lines). Please reference our prior report ([link](#)) for a more detailed overview on the basics of DRAM.

What are the key challenges faced by current $6F^2$ DRAM architecture?

While maintaining a $6F^2$ cell to area ratio for some time, the industry has been able to improve DRAM density by reducing the half pitch (i.e. node shrinks). In doing so, this has allowed for more and more DRAM cells to be densely packed on a DRAM chip (or IC). While smaller DRAM cell sizes (scaling) has enabled cost per bit reduction, performance increase and in turn application demand growth, this has also come at the expense of several growing challenges:

- **Current/charge leakage:** DRAM devices need to meet requirements for cell charges while pre-empting excessive current leakage - i.e. finding a balance. For the capacitor, maintaining sufficient capacitance becomes difficult as cell size shrinks - resulting in data loss requiring higher refresh cycles. The ratio of bit-line capacitance to cell capacitance is becoming higher as feature sizes decrease (representing an increase in resistance). This, in turn, slows down cell operation and leads to a worse bit-line sensing margin - which impacts performance when the current discharges.
- **Reliability:** A DRAM IC, when exposed to magnetic interference within a system can "flip" to the opposite state – ie. recording a "0" instead of a "1" and vice versa. This issue gets worse with smaller features as metal lines connecting different parts of a chip get closer together resulting in higher resistance and parasitic capacitance - causing signal interference, power consumption issues.
- **Structure issues:** To resolve issues around charge leakage, low cell capacitance etc., memory makers have increasingly begun adopting different process steps using different equipment and materials for critical layers. This brings about additional challenges on its own - creating uniform trenches for capacitors using high-aspect ratio etch, managing thermal properties while using different mix of low/high-k and silicon / metal materials, etc.
- **Scaling difficulties:** All the above mentioned issues come together in limiting vendors to scale DRAM production in an economically feasible way, whilst reaching the performance required for the device. This has contributed to slower cost per bit reduction over time for DRAM vendors. While introduction of processes such as EUV lithography (allows for reduction of certain process steps post patterning) has contributed to addressing some challenges, we note that EUV alone doesn't address the challenges stemming from shrinking DRAM cell sizes.

Given the increasing difficulties associated with controlling the above variables on a $6F^2$ design while continuing with tech process migration, we believe the **DRAM industry may be working on transitioning to a smaller DRAM cell to area ratio - i.e. $4F^2$ cell to area ratio.**

What is 4F² or Vertical Channel Access Transistor (VCAT) DRAM?

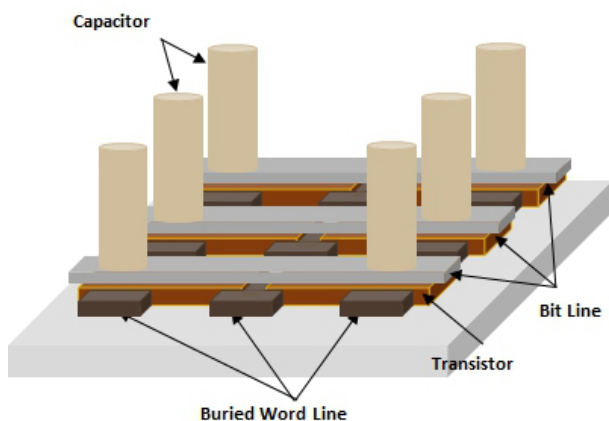
For the current 6F² DRAM architecture, the capacitor pillar sits on top of the transistor in a DRAM cell. Given the challenges associated with further cell miniaturization under this architecture, one idea has been to **get to a smaller DRAM cell size or 4F² by adopting a vertical channel access transistor design.**

In layman terms, this approach aims to reduce the size of the DRAM cell by **installing the transistor (wrapped) around the capacitor in a vertical cylindrical channel.** In effect, **this approach combines a stacked capacitor with a surrounding gate vertical channel access transistor (VCAT).**

The main benefit of transitioning to 4F² DRAM comes from higher density combined with the benefit of relaxed design rules (versus continuing migration at 6F²). The cell area saved by moving the DRAM transistor around the capacitor can be used to install additional capacitor channels - i.e. more DRAM cells per area array - while the wrapped transistor design also helps with capacitance. This is positive for both performance and costs.

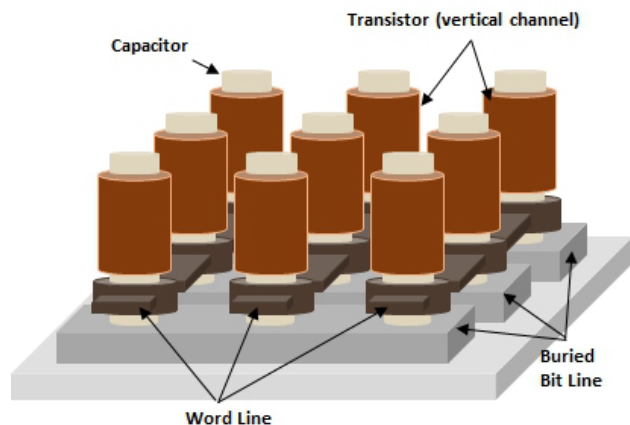
- **Higher memory capacity/density:** As seen in Figure 2, the transition to 4F² allows DRAM makers to fit more cells in a given array (6 cells for 6F² to 9 for 4F²). This helps DRAM makers achieve higher memory capacity and density. All factors held equal, moving to 4F² should in theory result in a one-time density gain of up to c. 50%.
- **Lower parasitic capacitance:** Parasitic capacitance refers to undesirable capacitance from two or more conductive elements being physically close to one another. By wrapping the transistor around the capacitor in a vertical channel, this results in one point of contact with the word line vs multiple points in 6F².
- **Relaxation of design rules:** Securing higher memory density as a result of a change in architecture (vs node shrink, which often entails thinning capacitor walls etc.) should allow memory makers to relax some design rules. **The aspect ratio of the capacitor may be less pronounced, ie less tall / thin. This is because the VCAT itself helps boost the performance of the device.** In turn, this should help in controlling the thickness of ALD metal layers such as for TiN and tungsten, and ease high aspect ratio etching processes.

Figure 1: Cross section of 6F² DRAM



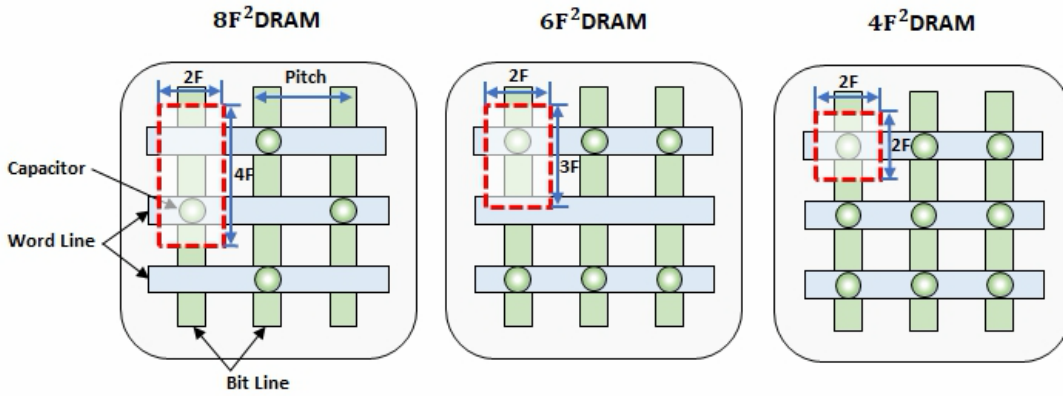
Source: UBS

Figure 2: Cross section of 4F² VCAT DRAM



Source: UBS

Figure 3: DRAM cell size comparison across architectures

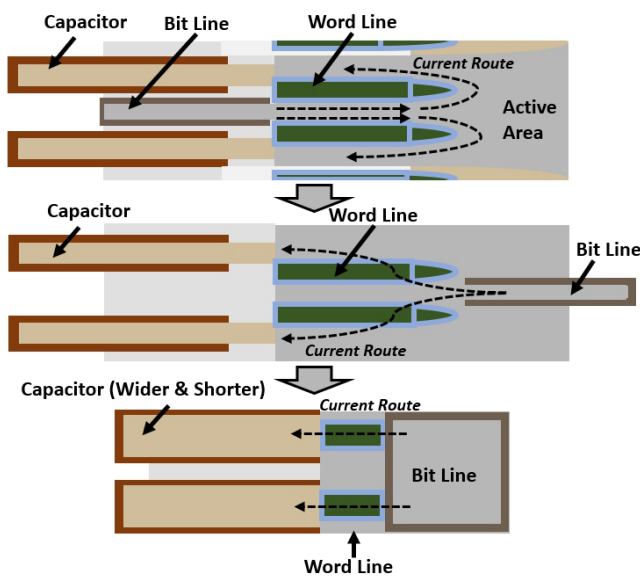


Source: UBS Research

How is 4F2 different from 3D (Stacked) DRAM?

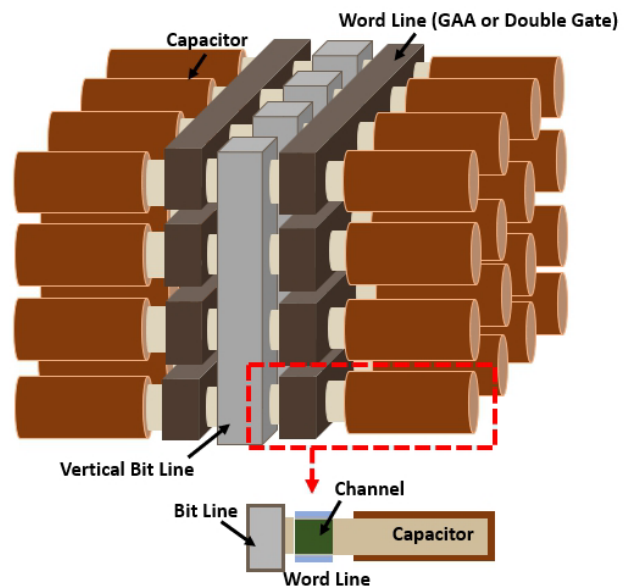
In addition to 4F² VCAT DRAM, we believe the industry was also initially exploring 3D DRAM (DRAM array 'turned over' 90 degrees similar to 3D NAND with the capacitor on its side). That said, our latest conversations with industry and experts suggest, while there may be a need to transition to a stacked DRAM solution when cell density becomes too dense even at 4F², **the immediate difficulties from a structural perspective (high aspect ratio lateral etch / epi growth + floating body effect control) make 3D DRAM unpractical**. As a result we believe all key DRAM vendors may have selected 4F² DRAM as the next technology roadmap after 6F² - to be discussed in more detail later.

Figure 4: Possible architecture change from 2D planar DRAM to 3D stacked DRAM



Source: UBS, LAM Research

Figure 5: Cross section of 3D 'stacked' DRAM



Source: UBS, Samsung

What are some of the key challenges associated with 4F2 adoption?

While 4F² maintains similar design properties as 6F², such as vertical capacitor channels (versus perhaps a 3D stacked DRAM design), changing the transistor layout in a vertical channel formation brings about incremental challenges that need to be addressed by industry before introduction. We highlight below some of the key challenges associated with 4F².

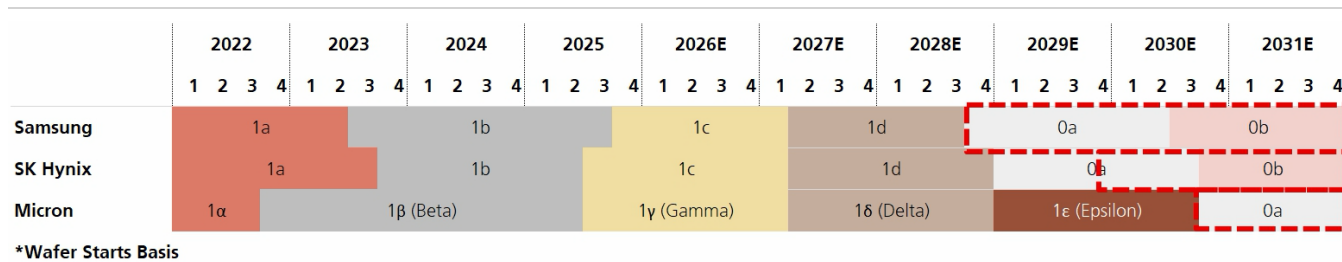
- **Structural design - floating body effect (FBE)**: One of the main challenges associated with 4F² comes from having a vertical transistor pillar isolated from the bottom substrate. The issue associated with this design is that charges may accumulate in between the source and drain which could cause charge/data retention loss and parasitic capacitance. To reduce this effect, we believe the industry may be looking at designs including additional back gates.
- **Manufacturing complexity - selective epi / hybrid bonding**: We believe 4F² may require incrementally more selective epi steps as well as new steps like hybrid bonding. In addition to building up silicon channels using selective epi (challenges in throughput and uniformity) this will also need to be built on top of the bit line which would require back side metal grinding + deposition and SOI wafers. As a result we believe industry maybe assessing the option of manufacturing the silicon channel and bit line on separate wafers (similar to cell / peri for 3D NAND) and bonding them together using W2W hybrid bonding.
- **One-time relaxation but doesn't alter patterning needs**: While the 1st generation of 4F² should in theory result in a one-time relaxation in design rules (we believe by about 2 generation equivalent), we note that it doesn't fundamentally change the architecture design. As a result, for subsequent 4F² nodes, difficulties associated with litho patterning - eventually requiring move to high-numerical aperture (NA) EUV - will continue.
- **Changes in design requiring changes to material sets**: Along with the increase in ALD process steps for 4F², we believe new materials will need to be developed as well. For gate materials, we believe industry may be looking into using molybdenum or ruthenium instead of current titanium nitride/tungsten to reduce resistance. In addition, we believe new high-K dielectric materials are also under development the the vertical pillars with replacement materials (to silicon channel) also in works for potential IGZO channel.

What is the timeline for 4F² adoption, and why does it matter?

Post numerous industry checks and expert calls, **we believe among DRAM vendors, Samsung may be the first to adopt 4F² starting from 0a nm (MP starting 2H28) with SK Hynix either following suit at 0a nm or 1 gen later, and Micron potentially after 1-epsilon.** Given that for Samsung, we now expect 1d nm will be the last 6F² node (MP in 2Q27) before transitioning to 4F², this would imply visibility on 0a nm 4F² related equipment shipments / engineering samples emerging into 2H27 followed by MP into 2H28. This is in-line with recent commentary from wafer fab equipment vendors indicating visibility on initial 4F² equipment coming through for late-2027/early-2028, marking a pull-in vs. our prior expectations of late-2028/2029 ([link](#)).

- **Samsung**: We believe Samsung has been the most aggressive out of the three DRAM players in pushing for 4F² and is targeting to adopt the technology starting from 0a nm (sampling in 2H27 before MP starting in 2H28). Versus our prior expectation, this marks a pull-in of adoption timeline by about 1 year.
- **SK Hynix**: SK Hynix is trying to keep 0a nm on 6F². That said, we believe the 4F² route may be the more likely outcome with sampling potentially beginning late-2028/2029 about 1-year after Samsung.
- **Micron**: We believe Micron may have been more active in assessing 3D DRAM (given less EUV requirement) but may have put 4F² back on their tech roadmap recently. Our checks suggest that, for this reason, Micron may be slightly behind than their peers in preparation for 4F², which may come at 0a nm after 1 epsilon being the last 6F² node.

Figure 6: DRAM tech migration and expected 4F² adoption roadmap for mass production



Source: UBS

4F² potentially more of a game changer for Samsung

We believe successful execution of 4F² may be particularly important for Samsung than peers and may explain the reason for the pull-in of timing. For Samsung, having faced technological issues over the last several DRAM nodes (we believe primarily related to design of capacitor walls being too thin/tall) has led them to undergo several redesigns, in turn impacting so far HBM execution. That said (if executed correctly), 4F² could offer a window for Samsung to redesign / relax design rules and help reset overall DRAM and HBM execution.

As highlighted via our previous UBS Evidence Lab patent tracker analysis back in 2022 ([link](#)) and as well based on our recent industry and expert checks, **we believe there is a visible gap between Samsung and the other two DRAM players** in terms of a 4F² R&D and technology readiness perspective which reads through as positive for Samsung's 4F² transition.

Figure 7: Samsung DRAM technology roadmap - base case

	1a nm	1b nm	1c nm	1d nm	0a nm	0b nm
Half pitch	13.8 nm	12.5 nm	11 nm	10 nm	9.x nm	9.x/8.x nm
Mass production	3Q21	3Q23	4Q25	2Q27E	2H28E	2H30E
EUV litho	Yes	Yes	Yes	Yes	Yes	Yes
Number of EUV layers	5 layers	5 layers	8 layers	10-12 layers	< 12 layers	TBD
Numerical aperture (NA)	0.33 NA	0.33 NA	0.33 NA	0.33 NA	0.33 NA	0.55 NA
Channel transistor	6F2	6F2	6F2	6F2	4F2	4F2

Source: Company data, UBS estimates

Figure 8: SK Hynix DRAM technology roadmap - base case

	1a nm	1b nm	1c nm	1d nm	0a nm	0b nm
Half pitch	14.7 nm	12.7 nm	11 nm	10 nm	9.x nm	9.x/8.x nm
Mass production	3Q21	4Q23	3Q25	2Q27E	1H29E	2H30E
EUV litho	Yes	Yes	Yes	Yes	Yes	Yes
Number of EUV layers	1 layer	4 layers	6 layers	c. 10 layers	TBD	TBD
Numerical aperture (NA)	0.33 NA	0.33 NA	0.33 NA	0.33 NA	0.33 NA	0.33/0.55 NA
Channel transistor	6F2	6F2	6F2	6F2	6F2/4F2	4F2

Source: Company data, UBS estimates

Figure 9: Micron DRAM technology roadmap - base case

	1α nm	1β nm	1γ nm	1δ nm	1ε nm	0a nm
Half pitch	14.6 nm	13.0 nm	12 nm	11 nm	10 nm	9.x nm
Mass production	4Q20	4Q22	3Q25	2Q27E	1H29E	2H30E
EUV litho	No	No	Yes	Yes	Yes	Yes
Number of EUV layers	-	-	1 layer	1 layer	c. 3 layers	TBD
Numerical aperture (NA)	-	-	0.33 NA	0.33 NA	0.33 NA	0.33 / 0.55 NA
Channel transistor	6F2	6F2	6F2	6F2	6F2	4F2

Source: Company data, UBS estimates

Move to 4F² offers a 'one-time' reset but scaling to continue afterwards

While transition to 4F² will offer help increase density as well as improve capacitance, we note that unlike 3D NAND flash, this will ultimately be a one-time reset / relaxation of design rules. Hence beyond the first generation of DRAM node adopting 4F² (in the case for Samsung 0a nm), scaling will likely need to continue in normal course with half-pitch continuing to be brought down.

Though still early days, industry checks and expert calls suggest that **4F² will likely continue to be the mainstream DRAM process technology following 6F² for potentially c. 3-4 nodes** as the reset to 4F² will potentially relax design rules by c. 30% or about 2 generations. This would imply the first 4F² 0a nm may have capacitor wall dimension similar to 1c nm and allow for process migration to continue. In fact, in order to make 4F² economically viable, we believe: 1/ 3-4 nodes are needed; 2/ and in order to achieve this, **high NA EUV will be required**. On one hand, making high NA EUV cost-efficient would imply adoption for 2-3 nodes. On the other hand, **high NA EUV may only come by 0b nm though as managing two key process changes (high NA EUV and 4F²) at the same time present executions risks**.

At some point next decade, we expect 3D DRAM to become an option. Even so, we believe a transition to 3D DRAM may not be simple given:

- **Design challenges:** Stacking DRAM in a 3D manner will aggravate issues such as floating body effect (distance to gate longer as you stack), potentially risking current leakage. Given a horizontal stacked structure, in theory the bit line will need to be designed vertically - potentially creating sensing margin differences between the top and bottom DRAM cell.
- **China competition:** 3D DRAM may open doors to Chinese competitors as it may potentially reduce the need for some traditional lithography steps (EUV equipment) that Chinese players do not have access to.
- **Cost challenges:** Memory makers will ultimately weigh the incremental density gains as a result of transitioning to 3D DRAM vs cost before making a decision. By the time DRAM vendors may need to transition to 3D stacked DRAM, it may require the stacking of 150 layers to get to equivalent density.

What are the implications of 4F² for DRAM equipment vendors?

Though not as meaningful as the transition to 3D NAND flash, we believe the transition to 4F² DRAM will offer opportunities for DRAM equipment vendors:

Semiscap Equipment: For wafer fab equipment (WFE) spend, with 4F² requiring a one-time reset in DRAM density, we believe this will offer the biggest incremental spending requirements for deposition and etch tools. In particular: selective epitaxial growth (SEG), atomic layer deposition, rapid thermal processing, high aspect ratio etching as well as potentially hybrid bonding.

- **Selective Epitaxial Growth (SEG):** We believe SEG will be needed to grow out the vertical channel transistors for 4F² vs a planar transistor structure for 6F². SEG using a single-crystal silicon allows for better control of potential dislocations and

grain boundaries that might occur with non-epi deposition which could result in charge leakages. Given that epitaxy is currently used in limited process steps (i.e. drain) for 6F², we believe this would make SEG potentially one of the most important incremental changes in process flow. **We note that key epi equipment providers include AMAT, TEL, ASMI and Eugene Tech.**

- **Atomic Layer Deposition (ALD):** Though not as incremental in terms of intensity versus SEG, we note that more ALD tools will also be required for 4F² given the increase in the number of vertical capacitors that will need to be built up. We note that 4F² may also require changes in the deposited metal/material that would also require changes to ALD process flow. **We note that key DRAM ALD equipment providers include AMAT, TEL, ASMI, Eugene Tech.**
- **Etching:** With the increase in the number of capacitor density per cell area, we believe that this will also necessitate the increase in spending required for etch. While relaxation in design rules (potentially allowing for thicker capacitor wall) may alleviate etch parameters on X/Y dimension, the emphasis and need to build higher pillars (Z dimension) will bring about challenges for tilt/leaning that will require higher aspect ratio etching as well as conductor etching. **We note that key DRAM etching equipment providers include LRCX, TEL and AMAT.**
- **Hybrid Bonding:** Though not finalized, we believe DRAM vendors may be weighing the option of adopting W2W hybrid bonding for 4F² DRAM. This may potentially be required to bond the silicon channel wafer together with a bit line wafer. We believe the other option may be to build up silicon channel on one side of wafer and deposit the bit line on the other side using backside metal deposition - the later requiring backside grinding, tempo bonding/debonding steps. **Similar to W2W hybrid bonding used in NAND flash, we believe TEL maybe engaged on this opportunity.**

Litho intensity to initially take a step back with 4F² but scaling for subsequent nodes required

We believe lithography intensity maybe kept constant or even take a step back during the initial transition to 4F² given DRAM vendors typically opt to minimize incremental changes (equating to risk) in process flow. That said, **after a one-time relax, we believe litho shrink and eventually high NA EUV will be necessary for subsequent nodes (8-9 nm).**

The longevity of 4F² DRAM, before requiring transition to 3D stacked DRAM, may also have implications on the timing of high-NA EUV adoption. Current industry consensus suggests that 4F² DRAM may last for c. 3-4 nodes, with the last few nodes likely necessitating high-NA EUV. That said, high-NA EUV may prove to be too expensive a process to use just for 1-2 nodes (the onus for Samsung less so given Foundry business) and as a result may influence earlier adoption of high-NA EUV (potentially post initial 4F² adoption), to spread out costs and go through the learning curve to manage yield/cost down. **Hence our base case is for high NA EUV to come in for 4F² at 0b nm and for c. 3 nodes.**

Valuation Method and Risk Statement

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Sell	FSR is > 6% below the MRA.	7%	25%
Short-Term Rating	Definition	Coverage ³	IB Services ⁴
Buy	Stock price expected to rise within three months from the time the rating was assigned because of a specific catalyst or event.	<1%	<1%
Sell	Stock price expected to fall within three months from the time the rating was assigned because of a specific catalyst or event.	<1%	<1%

Source: UBS. Rating allocations are as of 31 December 2025.

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Company Name	Reuters	12-month rating	Price	Price date
ASM International ²⁸	ASMI.AS	Buy	€620.20	13 Jan 2026
ASML ^{16,28}	ASML.AS	Buy	€1,102.6	13 Jan 2026
Air Liquide ²⁸	AIRP.PA	Buy	€157.96	13 Jan 2026
Applied Materials Inc ^{16,28,8,20}	AMAT.O	Buy (CBE)	US\$304.87	13 Jan 2026
Entegris Inc ^{16,28,20}	ENTG.O	Neutral (CBE)	US\$102.07	13 Jan 2026
Eugene Technology	084370.KQ	Buy	Won84,100	14 Jan 2026
Hansol Chemical	014680.KS	Buy	Won240,000	14 Jan 2026
LAM Research Corp ^{16,28,8}	LRCX.O	Buy	US\$214.38	13 Jan 2026
Merck KGaA ^{12,28}	MRCG.DE	Buy	€128.75	13 Jan 2026
SK Hynix ^{28,8}	000660.KS	Buy	Won742,000	14 Jan 2026
Samsung Electronics ^{28,8}	005930.KS	Buy	Won140,300	14 Jan 2026
Tokyo Electron ²⁸	8035.T	Buy	¥42,310	14 Jan 2026

Source: UBS Global Research; LSEG Eikon. All prices as of local market close. Ratings in this table are the most current published ratings prior to this report. They may be more recent than the stock pricing date.

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