

CLAIMS

1. A method of etching a substrate, comprising:

(a) receiving a substrate having material for removal thereon in a reaction chamber of a reactor, wherein the reactor comprises:

(i) an upper sub-chamber and a lower sub-chamber,

(ii) a grid assembly positioned in the reaction chamber and thereby dividing the reaction chamber into the upper sub-chamber and the lower sub-chamber, wherein the grid assembly comprises at least an uppermost grid and a lowermost grid, wherein the uppermost and lowermost grids are connected with one or more power supplies for independently providing negative bias to the grids, and wherein each grid of the grid assembly has perforations extending through the thickness of the grid,

(iii) one or more inlets to the upper sub-chamber,

(iv) one or more inlets to the lower sub-chamber, and

(v) a plasma generation source designed or configured to produce a plasma in the upper sub-chamber,

(b) supplying a plasma generating gas to the upper sub-chamber and generating a plasma from the plasma generating gas,

(c) applying a negative bias to at least the uppermost and lowermost grids of the grid assembly, wherein the bias applied to the lowermost grid is more negative than the bias applied to the uppermost grid,

(d) supplying an etching gas to the lower sub-chamber through the one or more inlets to the lower sub-chamber, and

(e) etching the substrate to remove at least a portion of the material for removal, wherein the lower sub-chamber is substantially free of plasma during operations (a)-(e).

2. The method of claim 1, wherein the bias applied to the uppermost grid is between about -0.5 to -50 V.

3. The method of claim 1, wherein the bias applied to the lowermost grid is between about -0.5 to -2000 V.
4. The method of claim 1, further comprising changing the bias applied to at least one grid of the grid assembly during operation (c).
5. The method of claim 1, wherein the etching gas in operation (d) is supplied in pulses.
6. The method of claim 1, wherein the plasma generating gas comprises a reactive gas.
7. The method of claim 1, further comprising supplying a processing gas to the lower sub-chamber and reacting the processing gas with the material for removal to form a reacted layer for removal comprising a material selected from the group consisting of an oxide, a nitride, a hydride, a chloride, a fluoride, organometallic complexes, or a combination thereof.
8. The method of claim 7, further comprising reacting the reacted layer for removal with the etching gas to remove the reacted layer for removal.
9. The method of claim 1, further comprising moving at least one grid of the grid assembly during at least one of operations (b)-(e).
10. The method of claim 1, wherein ions present in the upper sub-chamber accelerate through the grid assembly and interact with a surface of the substrate.
11. A method of etching a substrate, comprising:
 - (a) generating a plasma in an upper region of a plasma reactor;
 - (b) accelerating ions from the plasma onto a surface of the substrate in a lower region of the plasma reactor, wherein the plasma does not contact the substrate;
 - (c) delivering an etchant gas to a surface of the substrate where the etchant gas reacts to etch metal or semiconductor from the surface and produce a volatile byproduct containing one or more atoms of the metal or semiconductor and one or more ligands from the etchant gas; and
 - (d) removing the volatile byproduct from the plasma reactor without having the byproduct substantially contact the plasma and without having the volatile byproduct substantially dissociate to a less volatile material.

12. The method of claim 11, wherein the etchant gas reacts in (c) to etch a metal selected from the group consisting of Fe, Mn, Ni, Mg, Pt, Pd, Co, Ru, Cu, Ir, and a combination thereof.
13. A method of etching a substrate, comprising:
- (a) receiving a substrate having removable material in a reaction chamber of a reactor,
 - (b) supplying a plasma generating gas above a grid assembly in the reaction chamber, the grid assembly comprising an uppermost grid and a lowermost grid, and generating a plasma from the plasma generating gas above the grid assembly,
 - (c) simultaneously applying a first negative bias and a second negative bias respectively to the uppermost and lowermost grids of the grid assembly, wherein the second negative bias applied to the lowermost grid is more negative than the first negative bias applied to the uppermost grid, and accelerating ions from the plasma through the grid assembly toward the substrate,
 - (d) supplying an etching gas below the grid assembly, and
 - (e) etching the substrate to remove at least a portion of the removable material,
- wherein an area below the grid assembly is substantially free of plasma during operations (a)-(e).
14. The method of claim 13, wherein the first negative bias applied to the uppermost grid is between about -0.5 to -50 V.
15. The method of claim 13, wherein the second negative bias applied to the lowermost grid is between about -0.5 to -2000 V.
16. The method of claim 13, further comprising changing at least one of the first negative bias and the second negative bias during operation (c).
17. The method of claim 13, wherein the etching gas in operation (d) is supplied in pulses.
18. The method of claim 13, wherein the plasma generating gas comprises an inert gas.
19. The method of claim 13, wherein the plasma generating gas comprises a reactive gas.

20. The method of claim 13, wherein the removable material is selected from the group consisting of Fe, Mn, Ni, Mg, Pt, Pd, Co, Ru, Cu, Ir, and a combination thereof.
21. The method of claim 13, further comprising supplying a processing gas to the area below the grid assembly and reacting the processing gas with the removable material to form a reacted removable layer comprising a material selected from the group consisting of an oxide, a nitride, a hydride, a chloride, a fluoride, organometallic complexes, or a combination thereof.
22. The method of claim 21, further comprising reacting the reacted removable layer with the etching gas to remove the reacted removable layer.
23. The method of claim 13, further comprising moving at least one of the uppermost grid and the lowermost grid during at least one of operations (b)-(e).
24. The method of claim 23, wherein moving at least one of the uppermost grid and the lowermost grid results in a greater flux of ions to the substrate compared to prior to moving at least one of the uppermost grid and the lowermost grid.
25. The method of claim 23, wherein moving at least one of the uppermost grid and the lowermost grid results in a lower flux of ions to the substrate compared to prior to moving at least one of the uppermost grid and the lowermost grid.
26. The method of claim 23, wherein an ion flux on the substrate comprises a first ion flux near a center region of the substrate and a second ion flux toward a periphery of the substrate, wherein moving at least one of the uppermost grid and lowermost grid results in an increase in the first ion flux and a decrease in the second ion flux.
27. The method of claim 23, wherein an ion flux on the substrate comprises a first ion flux near a center region of the substrate and a second ion flux toward a periphery of the substrate, wherein moving at least one of the uppermost grid and the lowermost grid results in a decrease in the first ion flux and an increase in the second ion flux.
28. The method of claim 23, wherein moving at least one of the uppermost grid and the lowermost grid results in repeated pulsing of ion flux on the substrate.

29. The method of claim 28, wherein the ion flux on the substrate pulses between a first state and a second state, the first state being a high ion flux state and the second state being a low ion flux state.

30. The method of claim 29, wherein during the low ion flux state, there is no line of sight through the grid assembly, in a direction perpendicular to the uppermost and lowermost grids.

31. The method of claim 13, wherein the ions that accelerate through the grid assembly interact with a surface of the substrate.

32. The method of claim 13, wherein the first negative bias and the second negative bias applied respectively to the uppermost and lowermost grids are DC bias.

33. An apparatus for etching a substrate, comprising:

(a) a reaction chamber,

(b) a grid assembly positioned in the reaction chamber and thereby dividing the reaction chamber into an upper sub-chamber and a lower sub-chamber, wherein the grid assembly comprises at least an uppermost grid and a lowermost grid,

(c) electrical connections with at least the uppermost and lowermost grids of the grid assembly for independently providing negative bias to the uppermost and lowermost grids,

(d) one or more inlets to the upper sub-chamber,

(e) one or more inlets to the lower sub-chamber,

(f) a plasma generation source configured to produce a plasma in the upper sub-chamber,

(g) one or more gas outlets to the lower sub-chamber configured to remove gas from the lower sub-chamber, and

(h) a controller configured to provide instructions for:

(i) supplying a plasma generating gas to the upper sub-chamber and generating the plasma from the plasma generating gas,

(ii) applying a negative bias to at least the uppermost and lowermost grids of the grid assembly, wherein the bias applied to the lowermost grid is more negative than the

bias applied to the uppermost grid, and accelerating ions from the plasma in the upper sub-chamber through the grid assembly toward the substrate,

(iii) supplying an etching gas to the lower sub-chamber, and

(iv) etching the substrate to remove at least a portion of the material for removal, wherein the lower sub-chamber is substantially free of plasma during operations (i)-(iv).

34. The apparatus of claim 33, wherein the grid assembly is designed or configured to serve as one or more of the inlets in (c) and (d).

35. The apparatus of claim 33, wherein a ratio of the height of the upper sub-chamber to the height of the lower sub-chamber is between about 0.1-10.

36. The apparatus of claim 33, wherein the grid assembly is designed to provide different levels of ion flux to different portions of a substrate surface.

37. The apparatus of claim 33, wherein the grid assembly comprises cooling channels embedded in the assembly

38. The apparatus of claim 33, wherein at least one grid of the grid assembly is movable.

39. The apparatus of claim 38, wherein rotation of the movable grid results in a displacement of some amount of assembly open area from one portion of the grid assembly to another portion of the grid assembly.

40. The apparatus of claim 39, wherein when the grids of the grid assembly are in a first relative position, the grid assembly open area is more concentrated toward the center of the grid assembly compared to when the grids of the grid assembly are in a second relative position.

41. The apparatus of claim 38, wherein the grids of the grid assembly may be positioned in at least a first position and a second position relative to one another, wherein when the grids of the grid assembly are in the first position, the grid assembly has some amount of open area, and when the grids of the grid assembly are in the second position, the grid assembly has no open area.

42. The apparatus of claim 38, wherein the controller is further configured to provide instructions for moving the movable grid during (iv) to thereby achieve pulses of ion flux, wherein the ion flux pulses between a low ion flux state and a high ion flux state.
43. The apparatus of claim 42, wherein during the low ion flux state, the grid assembly has no open area, thereby ensuring that substantially no ions pass through the grid assembly.
44. The apparatus of claim 33, wherein the plasma generation source comprises one or more plasma coils positioned above the upper sub-chamber.
45. The apparatus of claim 33, wherein the plasma generation source is a capacitively coupled plasma source.
46. The apparatus of claim 33, wherein the grid assembly comprises more than two grids.
47. The apparatus of claim 33, wherein the grids of the grid assembly are separated by distance of about 5 mm or less.
48. The apparatus of claim of claim 33, wherein at least one of the uppermost and lowermost grids of the grid assembly comprises wires arranged in a grid-shape or a spiderweb-shape.
49. The apparatus of claim 33, wherein at least one grid of the grid assembly is non-planar.
50. The apparatus of claim 33, wherein each grid in the grid assembly comprises perforations extending through the thickness of the grid.
51. An apparatus for etching a substrate, comprising:
- (a) a reaction chamber,
 - (b) a grid assembly positioned in the reaction chamber and thereby dividing the reaction chamber into an upper region and a lower region, wherein the grid assembly comprises at least a first grid and a second grid,
 - (c) electrical connections with at least the first and second grids of the grid assembly for independently providing negative bias to the first and second grids,
 - (d) one or more inlets to the upper region of the reaction chamber,

(e) one or more inlets to the lower region of the reaction chamber,

(f) a plasma generation source configured to produce a plasma in the upper region of the reaction chamber,

(g) one or more gas outlets to the lower region of the reaction chamber, the outlet configured to remove gas from the lower region of the reaction chamber, and

(h) a controller configured to provide instructions for:

(i) generating the plasma in the upper region of the reaction chamber;

(ii) applying a first negative DC bias to the first grid in the grid assembly and applying a second negative DC bias to the second grid in the grid assembly, and accelerating ions from the plasma onto a surface of the substrate in the lower region of the reaction chamber, wherein the plasma does not contact the substrate;

(iii) delivering an etchant gas to the surface of the substrate, wherein the etchant gas reacts to etch metal or semiconductor from the surface of the substrate and thereby produce a volatile byproduct containing one or more atoms of the metal or semiconductor and one or more ligands from the etchant gas; and

(iv) removing the volatile byproduct from the reaction chamber without having the volatile byproduct substantially contact the plasma and without having the volatile byproduct substantially dissociate to a less volatile material.

52. The apparatus of claim 50, wherein the grid assembly comprises at least a third grid.

CLAIMS

What is claimed is:

1. A method of etching a substrate, comprising:
 - (a) receiving a substrate having material for removal thereon in a reaction chamber of a reactor, wherein the reactor comprises:
 - (i) an upper sub-chamber and a lower sub-chamber,
 - (ii) a grid assembly positioned in the reaction chamber and thereby dividing the reaction chamber into the upper sub-chamber and the lower sub-chamber, wherein the grid assembly comprises at least an uppermost grid and a lowermost grid, wherein the uppermost and lowermost grids are connected with one or more power supplies for independently providing negative bias to the grids, and wherein each grid of the grid assembly has perforations extending through the thickness of the grid,
 - (iii) one or more inlets to the upper sub-chamber,
 - (iv) one or more inlets to the lower sub-chamber, and
 - (v) a plasma generation source designed or configured to produce a plasma in the upper sub-chamber,
 - (b) supplying a plasma generating gas to the upper sub-chamber and generating a plasma from the plasma generating gas,
 - (c) applying a negative bias to at least the uppermost and lowermost grids of the grid assembly, wherein the bias applied to the lowermost grid is more negative than the bias applied to the uppermost grid,
 - (d) supplying an etching gas to the lower sub-chamber through the one or more inlets to the lower sub-chamber, and
 - (e) etching the substrate to remove at least a portion of the material for removal,wherein the lower sub-chamber is substantially free of plasma during operations (a)-(e).

2. The method of claim 1, wherein the bias applied to the uppermost grid is between about -0.5 to -50 V.
3. The method of claim 1, wherein the bias applied to the lowermost grid is between about -0.5 to -2000 V.
4. The method of claim 1, further comprising changing the bias applied to at least one grid of the grid assembly during operation (c).
5. The method of claim 1, wherein the etching gas in operation (d) is supplied in pulses.
6. The method of claim 1, wherein the plasma generating gas comprises an inert gas.
7. The method of claim 1, wherein the plasma generating gas comprises a reactive gas.
8. The method of claim 1, wherein the material for removal is selected from the group consisting of Fe, Mn, Ni, Mg, Pt, Pd, Co, Ru, Cu, Ir, and a combination thereof.
9. The method of claim 1, further comprising supplying a processing gas to the lower sub-chamber and reacting the processing gas with the material for removal to form a reacted layer for removal comprising a material selected from the group consisting of an oxide, a nitride, a hydride, a chloride, a fluoride, organometallic complexes, or a combination thereof.
10. The method of claim 9, further comprising reacting the reacted layer for removal with the etching gas to remove the reacted layer for removal.
11. The method of claim 1, further comprising moving at least one grid of the grid assembly during at least one of operations (b)-(e).
12. The method of claim 1, wherein ions present in the upper sub-chamber accelerate through the grid assembly and interact with a surface of the substrate.
13. A method of etching a substrate, comprising:
 - (a) generating a plasma in an upper region of a plasma reactor;
 - (b) accelerating ions from the plasma onto a surface of the substrate in a lower region of the plasma reactor, wherein the plasma does not contact the substrate;
 - (c) delivering an etchant gas to a surface of the substrate where the etchant gas reacts to etch metal or semiconductor from the surface and produce a volatile byproduct containing

one or more atoms of the metal or semiconductor and one or more ligands from the etchant gas; and

(d) removing the volatile byproduct from the plasma reactor without having the byproduct substantially contact the plasma and without having the volatile byproduct substantially dissociate to a less volatile material.

14. The method of claim 13, wherein accelerating the ions comprises applying a negative bias to one or more grids separating the upper and lower regions of the plasma reactor.

15. The method of claim 13, wherein the etchant gas reacts in (c) to etch a metal selected from the group consisting of Fe, Mn, Ni, Mg, Pt, Pd, Co, Ru, Cu, Ir, and a combination thereof.

16. An apparatus for etching a substrate, comprising:

(a) a reaction chamber,

(b) a grid assembly positioned in the reaction chamber and thereby dividing the reaction chamber into an upper sub-chamber and a lower sub-chamber, wherein the grid assembly comprises at least an uppermost grid and a lowermost grid, and wherein each grid in the grid assembly has perforations extending through the thickness of the grid,

(c) electrical connections with at least the uppermost and lowermost grids of the grid assembly for independently providing negative bias to the uppermost and lowermost grids,

(d) one or more gas inlets to the upper sub-chamber,

(e) one or more gas inlets to the lower sub-chamber,

(f) a plasma generation source designed or configured to produce a plasma in the upper sub-chamber,

(g) one or more gas outlets to the lower sub-chamber designed or configured to remove gas from the lower sub-chamber, and

(h) a controller designed or configured to provide instructions for:

(i) supplying a plasma generating gas to the upper sub-chamber and generating a plasma from the plasma generating gas,

(ii) applying a negative bias to at least the uppermost and lowermost grids of the grid assembly, wherein the bias applied to the lowermost grid is more negative than the bias applied to the uppermost grid, and

(iii) supplying an etching gas to the lower sub-chamber.

17. The apparatus of claim 16, wherein the grid assembly is designed or configured to serve as one or more of the inlets in (c) and (d).

18. The apparatus of claim 16, wherein a ratio of the height of the upper sub-chamber to the height of the lower sub-chamber is between about 0.1-10.

19. The apparatus of claim 16, wherein the grid assembly is designed to provide different levels of ion flux to different portions of a substrate surface.

20. The apparatus of claim 16, wherein the grid assembly comprises cooling channels embedded in the assembly

21. The apparatus of claim 16, wherein at least one grid of the grid assembly is movable.

22. The apparatus of claim 16, wherein the plasma generation source comprises one or more plasma coils positioned above the upper sub-chamber.

23. The apparatus of claim 16, wherein the plasma generation source is a capacitively coupled plasma source.

24. The apparatus of claim 16, wherein the grid assembly comprises more than two grids.