

CLAIMS

What is claimed is:

1. A digital twin of a process chamber of semiconductor manufacturing equipment, comprising one or more non-transitory machine-readable media comprising logic configured to implement:

a first model of a first location of the process chamber; and

a second model of a second location of the process chamber,

wherein the first model of the first location of the process chamber is coupled to the second model of the second location of the process chamber, and

wherein the first model of the first location of the process chamber and the second model of the second location of the process chamber are each of a model type that is one of:

1) an AI/ML model; 2) an HFS model; or 3) a closed-form solution, and

wherein the first model of the first location of the process chamber and the second model of the second location of the process chamber each represent a class of physical phenomena that is one of: 1) thermal characteristics; 2) plasma characteristics; 3) fluid dynamics; 4) structural characteristics; or 5) chemical reactions.

2. The digital twin of claim 1, wherein the first model of the first location of the process chamber is of a different model type than the second model of the second location of the process chamber.

3. The digital twin of any one of claim 1 or 2, wherein the first model of the first location of the process chamber represents a different class of physical phenomena than the second model of the second location of the process chamber.

4. The digital twin of any one of claim 1 or 2, wherein the first location is one of: 1) a pedestal of an ESC; 2) a showerhead; 3) a gap between the pedestal and the showerhead; 4) a chamber wall; or 5) a surface of a wafer fabricated by the process chamber.

5. The digital twin of any one of claim 1 or 2, wherein the first model of the first location of the process chamber being coupled to the second model of the second location of the process chamber comprises the first model of the first location of the process chamber

providing outputs to the second model of the second location of the process chamber for use by the second model of the second location of the process chamber.

6. The digital twin of claim 5, wherein the first model of the first location of the process chamber being coupled to the second model of the second location of the process chamber comprises the first model of the first location of the process chamber receiving outputs from the second model of the second location of the process chamber for use by the first model of the first location of the process chamber.

7. A computer program product for generating digital twins of process chambers, the computer program product comprising a non-transitory computer readable medium on which is provided computer-executable instructions for:

generating a digital twin by:

generating, for a first location of a process chamber, a plurality of High Fidelity Simulation (HFS) values using an HFS model of the first location of the process chamber;

receiving a plurality of sensor measurements corresponding to the first location of the process chamber;

training an Artificial Intelligence/Machine Learning (AI/ML) model of the first location of the process chamber using at least one of the plurality of HFS values and the plurality of sensor measurements; and

coupling the trained AI/ML model of the first location of the process chamber to a model of a second location of the process chamber, wherein the digital twin of the process chamber is comprised of the trained AI/ML model of the first location of the process chamber and the model of the second location of the process chamber.

8. The computer program product of claim 7, wherein the second model of the second location of the process chamber is one of: 1) an AI/ML model; 2) an HFS model; or 3) a closed-form solution.

9. The computer program product of any one of claim 7 or 8, wherein the HFS model of the first location of the process chamber and the AI/ML model of the first location of the process chamber both model a same class of physical phenomena.

10. The computer program product of any one of claim 7 or 8, wherein the trained AI/ML model of the first location of the process chamber and the model of the second location of the process chamber each model a class of physical phenomena.

11. The computer program product of claim 10, wherein the class of physical phenomena is one of: thermal characteristics, plasma characteristics, fluid dynamics, structural characteristics, or chemical reactions.

12. The computer program product of claim 10, wherein the trained AI/ML model of the first location of the process chamber and the model of the second location of the process chamber model different classes of physical phenomena.

13. The computer program product of any one of claim 7 or 8, wherein the HFS model of the first location of the process chamber generates simulation values with a timestep that is shorter than a timestep of the AI/ML model of the first location of the process chamber.

14. The computer program product of any one of claim 7 or 8, wherein the first location of the process chamber is one of: 1) a pedestal of an electrostatic chuck (ESC); 2) a showerhead; 3) a gap between the showerhead and the pedestal; 4) a chamber wall; or 5) a surface of a wafer fabricated by the process chamber.

15. The computer program product of any one of claim 7 or 8, wherein coupling the trained AI/ML model of the first location of the process chamber to the model of the second location of the process chamber comprises providing a plurality of outputs of the trained AI/ML model of the first location of the process chamber to the model of the second location of the process chamber.

16. The computer program product of claim 15, wherein providing the plurality of outputs of the trained AI/ML model of the first location of the process chamber to the model of the second location of the process chamber comprises:

waiting until the plurality of outputs of the trained AI/ML model of the first location of the process chamber have been received; and

transmitting the plurality of outputs to the model of the second location of the process chamber.

17. The computer program product of any one of claim 7 or 8, wherein coupling the trained AI/ML model of the first location of the process chamber to the model of the second location of the process chamber comprises providing a plurality of outputs of the model of the second location of the process chamber to the trained AI/ML model of the first location of the process chamber.

18. The computer program product of any one of claim 7 or 8, further comprising computer-executable instructions for validating a performance of the trained AI/ML model of the first location of the process chamber after inclusion of the trained AI/ML model of the first location of the process chamber in the digital twin.

19. The computer program product of claim 18, wherein validating the performance of the trained AI/ML model comprises:

generating simulated data using the digital twin that includes the trained AI/ML model of the first location of the process chamber and the model of the second location of the process chamber; and

comparing the simulated data to experimental data collected using a plurality of sensors associated with a physical process chamber.

20. The computer program product of any one of claim 7 or 8, wherein the model of the second location of the process chamber is an HFS model, and further comprising computer-executable instructions for replacing the HFS model of the second location of the process chamber with a trained AI/ML model of the second location in the digital twin.

21. A computer program product for using digital twins of process chambers, the computer program product comprising a non-transitory computer readable medium on which is provided computer-executable instructions for:

identifying a plurality of inputs to a digital twin of a process chamber, wherein the digital twin comprises a first model of a first location of the process chamber and a second model of a second location of the process chamber, and wherein the first model of the first location of the process chamber and the second model of the second location of the process

chamber are coupled, and wherein the plurality of inputs represent operating conditions of the process chamber;

providing the plurality of inputs to the digital twin; and

generating predicted wafer characteristics of a simulated wafer using the digital twin.

22. The computer program product of claim 21, wherein the first model of the first location of the process chamber includes specifications of a component of the process chamber, and further comprising computer-executable instructions for validating the specifications of the component based on the predicted wafer characteristics.

23. The computer program product of any one of claim 21 or 22, wherein the plurality of inputs include parameters of a recipe implemented by the process chamber, and further comprising computer-executable instructions for validating at least one parameter of the recipe based on the predicted wafer characteristics.

24. The computer program product of any one of claim 21 or 22, wherein the predicted wafer characteristics comprise an indication of a defect of the simulated wafer.

25. The computer program product of any one of claim 21 or 22, further comprising computer-executable instructions for identifying a recommendation to modify at least one operating condition of the operating conditions based on the predicted wafer characteristics.

26. The computer program product of claim 25, wherein the recommendation is identified in response to determining that the predicted wafer characteristics indicate a defect of the simulated wafer.

27. The computer program product of claim 25, wherein the recommendation is identified in response to determining that at least one of the first model and the second model has generated values that indicate anomalous operating conditions of the process chamber.