[0009] In some embodiments, a method for reducing ruthenium oxides on an EUV photomask may comprise flowing a reducing agent gas and a carrier gas into an atmospheric-pressure (AP) plasma generator in an EUV photomask processing chamber, generating a plasma above the EUV photomask with the AP plasma generator using an RF power source, and flowing the reducing agent gas and the carrier gas into the plasma and onto a top surface of the EUV photomask, wherein the reducing agent gas reacts with a ruthenium (Ru) oxide layer on a Ru capping layer to reduce the Ru oxide layer to Ru metal.

[0010] In some embodiments, the method may further include heating the EUV photomask to a temperature of approximately 100 degrees Celsius to approximately a thermal budget of the EUV photomask, wherein the thermal budget of the EUV photomask is approximately 150 degrees Celsius, wherein the plasma in the AP plasma generator is dielectric barrier discharge plasma, wherein the reducing agent gas is carbon monoxide gas, methane gas, or hydrogen gas and the carrier gas is argon gas, helium gas, or nitrogen gas, and/or wherein the RF power source operates at a frequency of 13.56MHz.

[0011] In some embodiments, an apparatus for reducing ruthenium oxides on an EUV photomask may comprise an EUV photomask processing chamber with a photomask support body attached to a photomask support, the photomask support body supporting an EUV photomask when present, a reducing agent gas supply fluidly connected to the EUV photomask processing chamber, a heater electrode in the photomask support body that is configured to heat the EUV photomask when present to a range of approximately 100 degrees Celsius to approximately 150 degrees Celsius, a first valve that controls a reducing agent gas that enters into the EUV photomask processing chamber, a second valve that controls effluent gases that exit the EUV photomask processing chamber, and a controller that regulates the first valve and the second valve to adjust a pressure inside of the EUV photomask processing chamber, wherein the pressure is adjustable from zero psi to 2500 psi and is adjusted, by the controller, to control a reduction rate to reduce RU oxides on a RU capping layer on the EUV photomask.

[0012] In some embodiments, an apparatus for reducing ruthenium oxides on an EUV photomask may comprise an EUV photomask processing chamber with a photomask support body attached to a photomask support, the photomask support

body supporting an EUV photomask when present, a reducing agent gas supply fluidly connected to the EUV photomask processing chamber, a carrier gas supply fluidly connected to the EUV photomask processing chamber, and a remote plasma generator fluidly connected to the EUV photomask processing chamber, wherein the remote plasma generator is configured to allow a reducing agent gas from the reducing agent gas supply and a carrier gas from the carrier gas supply flow through the remote plasma generator when plasma is generated in the remote plasma generator and subsequently allow the reducing agent gas, the carrier gas, and the plasma to flow into the EUV photomask processing chamber to interact with the EUV photomask when present to reduce RU oxides on a RU capping layer on the EUV photomask.

[0013] In some embodiments, the apparatus may further include a heater electrode in the photomask support body that is configured to heat the EUV photomask when present to a range of approximately 100 degrees Celsius to approximately 150 degrees Celsius to enhance a reduction rate of Ru oxides, a controller that regulates a reduction rate of the Ru oxides by regulating a power applied to the plasma in the remote plasma generator or by regulating a temperature of the EUV photomask when present by adjusting power to the heater electrode.

[0014] In some embodiments, an apparatus for reducing ruthenium oxides on an EUV photomask may comprise an EUV photomask processing chamber with a photomask support body attached to a photomask support, the photomask support body supporting an EUV photomask when present, a reducing agent gas supply fluidly connected to the EUV photomask processing chamber, a carrier gas supply fluidly connected to the EUV photomask processing chamber, and an atmospheric-pressure (AP) plasma generator in the EUV photomask processing chamber, wherein the AP plasma generator is configured to allow a reducing agent gas from the reducing agent gas supply and a carrier gas from the carrier gas supply to flow through the AP plasma generator when dielectric barrier discharge plasma is generated by the AP plasma generator directly above the EUV photomask and subsequently allow the reducing agent gas and the carrier gas to flow onto a top surface of the EUV photomask to reduce RU oxides on a RU capping layer on the EUV photomask.

[0015] In some embodiments, the apparatus may further include a heater electrode in the photomask support body that is configured to heat the EUV photomask when present to a range of approximately 100 degrees Celsius to approximately 150 degrees Celsius to enhance a reduction rate of Ru oxides and/or a controller that regulates a reduction rate of the Ru oxides by adjusting a power applied to the dielectric barrier discharge plasma in the AP plasma generator or by adjusting a temperature of the EUV photomask when present by adjusting power to the heater electrode.

[0016] Other and further embodiments are disclosed below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Embodiments of the present principles, briefly summarized above and discussed in greater detail below, can be understood by reference to the illustrative embodiments of the principles depicted in the appended drawings. However, the appended drawings illustrate only typical embodiments of the principles and are thus not to be considered limiting of scope, for the principles may admit to other equally effective embodiments.

[0018] Figure 1 depicts a top-down and cross-sectional view of an EUV photomask in accordance with some embodiments of the present principles.

[0019] Figure 2 is a method of reduction of Ru oxide in accordance with some embodiments of the present principles.

[0020] Figure 3 depicts a cross-sectional view of a photomask processing chamber in accordance with some embodiments of the present principles.

[0021] Figure 4 is a method of reduction of Ru oxide in accordance with some embodiments of the present principles.

[0022] Figure 5 depicts a cross-sectional view of a photomask processing chamber in accordance with some embodiments of the present principles.

[0023] Figure 6 is a method of reduction of Ru oxide in accordance with some embodiments of the present principles.

[0024] Figure 7 depicts a cross-sectional view of a photomask processing chamber in accordance with some embodiments of the present principles.

CLAIMS

1. A method for reducing ruthenium oxides on an extreme ultraviolet (EUV) photomask, comprising:

heating the EUV photomask with a ruthenium (Ru) capping layer with a top surface which has a Ru oxide layer to a temperature of approximately 100 degrees Celsius to approximately a thermal budget of the EUV photomask;

flowing a reducing agent gas into an EUV photomask processing chamber; and

pressurizing the EUV photomask processing chamber to a process pressure to increase a reducing reaction between the reducing agent gas and the Ru oxide layer on the Ru capping layer.

2. The method of claim 1, wherein the process pressure is from zero to approximately 150 psi.

3. The method of claim 1, wherein the process pressure is from zero to approximately 1500 psi.

4. The method of claim 1, wherein the EUV photomask processing chamber is a cylindrical chamber and the process pressure is from zero to approximately 2500 psi.

5. The method of claim 1, wherein the process pressure is obtained by regulating a flow of the reducing agent gas into the EUV photomask processing chamber and effluent gases out of the EUV photomask processing chamber.

6. The method of claim 1, wherein the reducing agent gas is carbon monoxide gas, methane gas, or hydrogen gas.

7. The method of claim 1, further comprising:

flowing a carrier gas along with the reducing agent gas, wherein the carrier gas reduces volatility of high concentrations of explosive reducing agent gases.

8. The method of claim 1, wherein the thermal budget of the EUV photomask is approximately 150 degrees Celsius.

9. A method for reducing ruthenium oxides on an extreme ultraviolet (EUV) photomask, comprising:

flowing a reducing agent gas and a carrier gas into a remote plasma generator;

generating a plasma in the remote plasma generator using an RF power source; and

flowing gases from the remote plasma generator into an EUV photomask processing chamber, wherein a remote plasma is formed above the EUV photomask to generate a self-bias on the EUV photomask and wherein the gases in the EUV photomask processing chamber react with a ruthenium (Ru) oxide layer on a Ru capping layer to reduce the Ru oxide layer to Ru metal.

10. The method of claim 9, wherein EUV photomask processing chamber operates in a vacuum.

11. The method of claim 9, wherein the plasma in the remote plasma generator is inductively coupled plasma.

12. The method of claim 9, wherein the reducing agent gas is carbon monoxide gas or methane gas and the carrier gas is argon gas, helium gas, or nitrogen gas.

13. The method of claim 9, wherein the RF power source operates at a frequency of 13.56MHz.

14. The method of claim 9, wherein the reducing agent gas is hydrogen gas and the remote plasma is adjusted to a sustainable level while providing a self-biasing power level of approximately 5eV such that implantation of atomic hydrogen into the Ru capping layer is prevented.

15. The method of claim 9, further comprising:

heating the EUV photomask to a temperature of approximately 100 degrees Celsius to approximately a thermal budget of the EUV photomask.

16. The method of claim 15, wherein the thermal budget of the EUV photomask is approximately 150 degrees Celsius.

17. A method for reducing ruthenium oxides on an extreme ultraviolet (EUV) photomask, comprising:

flowing a reducing agent gas and a carrier gas into an atmospheric-pressure (AP) plasma generator in an EUV photomask processing chamber;

generating a plasma above the EUV photomask with the AP plasma generator using an RF power source; and

flowing the reducing agent gas and the carrier gas into the plasma and onto a top surface of the EUV photomask, wherein the reducing agent gas reacts with a ruthenium (Ru) oxide layer on a Ru capping layer to reduce the Ru oxide layer to Ru metal.

18. The method of claim 17, further comprising:

heating the EUV photomask to a temperature of approximately 100 degrees Celsius to approximately a thermal budget of the EUV photomask.

19. The method of claim 18, wherein the thermal budget of the EUV photomask is approximately 150 degrees Celsius.

20. The method of claim 17, wherein the plasma in the AP plasma generator is dielectric barrier discharge plasma.

21. The method of claim 17, wherein the reducing agent gas is carbon monoxide gas, methane gas, or hydrogen gas and the carrier gas is argon gas, helium gas, or nitrogen gas.

22. The method of claim 17, wherein the RF power source operates at a frequency of 13.56MHz.

23. An apparatus for reducing ruthenium (RU) oxides on an extreme ultraviolet (EUV) photomask, comprising:

an EUV photomask processing chamber with a photomask support body attached to a photomask support, the photomask support body supporting an EUV photomask when present;

a reducing agent gas supply fluidly connected to the EUV photomask processing chamber;

a heater electrode in the photomask support body that is configured to heat the EUV photomask when present to a range of approximately 100 degrees Celsius to approximately 150 degrees Celsius;

a first valve that controls a reducing agent gas that enters into the EUV photomask processing chamber;

a second valve that controls effluent gases that exit the EUV photomask processing chamber; and

a controller that regulates the first valve and the second valve to adjust a pressure inside of the EUV photomask processing chamber, wherein the pressure is adjustable from zero psi to 2500 psi and is adjusted, by the controller, to control a reduction rate to reduce RU oxides on a RU capping layer on the EUV photomask.

24. An apparatus for reducing ruthenium (RU) oxides on an extreme ultraviolet (EUV) photomask, comprising:

an EUV photomask processing chamber with a photomask support body attached to a photomask support, the photomask support body supporting an EUV photomask when present;

a reducing agent gas supply fluidly connected to the EUV photomask processing chamber;

a carrier gas supply fluidly connected to the EUV photomask processing chamber; and

a remote plasma generator fluidly connected to the EUV photomask processing chamber, wherein the remote plasma generator is configured to allow a reducing agent gas from the reducing agent gas supply and a carrier gas from the carrier gas supply flow through the remote plasma generator when plasma is generated in the remote plasma generator and subsequently allow the reducing agent gas, the carrier gas, and the plasma to flow into the EUV photomask processing

chamber to interact with the EUV photomask when present to reduce RU oxides on a RU capping layer on the EUV photomask.

25. The apparatus of claim 24, further comprising:

a heater electrode in the photomask support body that is configured to heat the EUV photomask when present to a range of approximately 100 degrees Celsius to approximately 150 degrees Celsius to enhance a reduction rate of Ru oxides.

26. The apparatus of claim 25, further comprising:

a controller that regulates a reduction rate of the Ru oxides by regulating a power applied to the plasma in the remote plasma generator or by regulating a temperature of the EUV photomask when present by adjusting power to the heater electrode.

27. An apparatus for reducing ruthenium (RU) oxides on an extreme ultraviolet (EUV) photomask, comprising:

an EUV photomask processing chamber with a photomask support body attached to a photomask support, the photomask support body supporting an EUV photomask when present;

a reducing agent gas supply fluidly connected to the EUV photomask processing chamber;

a carrier gas supply fluidly connected to the EUV photomask processing chamber; and

an atmospheric-pressure (AP) plasma generator in the EUV photomask processing chamber, wherein the AP plasma generator is configured to allow a reducing agent gas from the reducing agent gas supply and a carrier gas from the carrier gas supply to flow through the AP plasma generator when dielectric barrier discharge plasma is generated by the AP plasma generator directly above the EUV photomask and subsequently allow the reducing agent gas and the carrier gas to flow onto a top surface of the EUV photomask to reduce RU oxides on a RU capping layer on the EUV photomask.

28. The apparatus of claim 27, further comprising:

a heater electrode in the photomask support body that is configured to heat the EUV photomask when present to a range of approximately 100 degrees Celsius to approximately 150 degrees Celsius to enhance a reduction rate of Ru oxides.

29. The apparatus of claim 28, further comprising:

a controller that regulates a reduction rate of the Ru oxides by adjusting a power applied to the dielectric barrier discharge plasma in the AP plasma generator or by adjusting a temperature of the EUV photomask when present by adjusting power to the heater electrode.