CLAIMS

1. A method for cleaning a semiconductor wafer comprising features of patterned structures, the method comprising:

applying liquid on the semiconductor wafer;

controlling, based on a timer, a power supply of a transducer to deliver acoustic energy to the liquid at a first frequency and a first power level for a predetermined first time period, wherein sizes of bubbles inside the features increase during the first time period; and

controlling, based on the timer, the power supply of the transducer to deliver acoustic energy to the liquid at a second frequency and a second power level for a predetermined second time period, wherein sizes of bubbles inside the features decrease during the second time period,

wherein the first and second time periods are alternately applied one after another for a predetermined number of cycles.

2. The method of claim 1, wherein the first time period is determined as a time period that achieves the best cleaning effect on the features.

3. The method of claim 2, wherein the first time period is determined by:

placing traceable impurities on the semiconductor wafer;

alternating between delivering acoustic energy to the liquid at the first frequency and the first power level for a test time period, and delivering acoustic energy to the liquid at the second frequency and the second power level for a sufficiently long time period;

measuring a cleaning effect on the traceable impurities;

repeating the above steps with a plurality of different test time periods; and

determining the first time period as the test time period with the best cleaning effect on the traceable impurities.

4. The method of claim 1, wherein the second time period is determined as a time period that achieves the best cleaning effect on the features.

5. The method of claim 4, wherein the second time period is determined by:

placing traceable impurities on the semiconductor wafer;

alternating between delivering acoustic energy to the liquid at the first frequency and the first power level for a predetermined time period, and delivering acoustic energy to the liquid at the second frequency and the second power level for a test time period;

measuring a cleaning effect on the traceable impurities;

repeating the above steps with a plurality of different test time periods; and

determining the second time period as the test time period with the best cleaning effect on the traceable impurities.

6. The method of claim 1, wherein the first time period ends prior to at least one of the features being blocked by the bubbles.

7. The method of claim 1, wherein the first time period ends after at least one of the features being blocked by the bubbles.

8. The method of claim 1, wherein the second power level is lower than the first power level.

9. The method of claim 8, wherein the second power level is zero.

10. The method of claim 1, wherein the second frequency is higher than the first frequency.

11. The method of claim 1, wherein acoustic energy in the second time period is in antiphase to acoustic energy in the first time period.

12. The method of claim 1, wherein the first frequency is equal to the second frequency, while the first power level is higher than the second power level.

13. The method of claim 1, wherein the first frequency is higher than the second frequency, while the first power level is higher than the second power level.

14. The method of claim 1, wherein the first frequency is lower than the second frequency, while the first power level is equal to the second power level.

15. The method of claim 1, wherein the first frequency is lower than the second frequency, while the first power level is higher than the second power level.

16. The method of claim 1, wherein the first frequency is lower than the second frequency, while the first power lever is lower than the second power level.

17. The method of claim 1, wherein the first power level rises during the first time period.

18. The method of claim 1, wherein the first power level falls during the first time period.

19. The method of claim 1, wherein the first power level both rises and falls during the first time period.

20. The method of claim 1, wherein the first frequency changes from a higher value to a lower value during the first time period.

21. The method of claim 1, wherein the first frequency changes from a lower value to a higher value during the first time period.

22. The method of claim 1, wherein the first frequency changes from a lower value to a higher value and then back to the lower value during the first time period.

23. The method of claim 1, wherein the first frequency changes from a higher value to a lower value and then back to the higher value during the first time period.

24. The method of claim 1, wherein the first frequency is set as f_1 first, f_3 later and f_4 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

25. The method of claim 1, wherein the first frequency is set as f_4 first, f_3 later and f_1 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

26. The method of claim 1, wherein the first frequency is set as f_1 first, f_4 later and f_3 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

27. The method of claim 1, wherein the first frequency is set as f_3 first, f_4 later and f_1 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

28. The method of claim 1, wherein the first frequency is set as f_3 first, f_1 later and f_4 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

29. The method of claim 1, wherein the first frequency is set as f_4 first, f_1 later and f_3 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

30. The method of claim 1, wherein the second frequency is zero and the second power level remains a constant positive value during the second time period.

31. The method of claim 1, wherein the second frequency is zero and the second power level remains a constant negative value during the second time period.

32. The method of claim 1, wherein the features comprise vias or trenches having depth to width ratios of at least 3.

33. The method of claim 1, wherein a device manufacturing node of the semiconductor wafer is no more than 16 nanometers.

34. The method of claim 1, further comprising rotating the wafer with respect to the transducer as acoustic energy is delivered.

35. The method of claim 1, wherein the second time period ends after a ratio of total bubble volume inside the features falls much lower than a cavitation saturation point.

36. The method of claim 1, wherein the first time period ends before a ratio of total bubble volume inside the features reaches a cavitation saturation point.

37. The method of claim 1, wherein the first time period ends when a ratio of total bubble volume inside the features reaches a cavitation saturation point.

38. The method of claim 1, wherein a duration of the first time period is $m\tau_1$, where τ_1 is the time for a ratio of total bubble volume inside the features reaches a cavitation saturation point.

39. The method of claim 38, wherein m is a value between 0.1 to 100.

40. The method of claim 1, wherein temperatures inside the bubbles decrease in the second time period.

41. The method of claim 40, wherein temperatures inside the bubble decrease to near a temperature of said liquid in the second time period.

42. The method of claim 1, wherein the first time period is shorter than 2,000 times of a cycle period of the first frequency.

43. The method of claim 1, wherein the first time period is shorter than $((V_i - V_0 - \Delta V)/(\Delta V - \delta V) + 1)/f_1$, where V_i is a desired volume, V_0 is an original volume, ΔV is a volume compression of the bubble after one time of compression, δV is a volume increase of the bubble after one time of expansion, and f1 is the first frequency.

44. An apparatus for cleaning a semiconductor wafer comprising features of patterned structures, the apparatus comprising:

a wafer holder configured to hold the semiconductor wafer;

an inlet configured to apply liquid on the semiconductor wafer;

a transducer configured to deliver acoustic energy to the liquid;

a power supply of the transducer; and

a controller for the power supply comprising a timer, the controller being configured to control the transducer based on the timer to:

deliver acoustic energy to the liquid at a first frequency and a first power level for a predetermined first time period, wherein sizes of bubbles inside the features increase during the first time period, and

deliver acoustic energy to the liquid at a second frequency and a second power level for a predetermined second time period, wherein sizes of bubbles inside the features decrease during the second time period,

wherein the controller is configured to alternately apply the first and second time periods one after another for a predetermined number of cycles.

45. The apparatus of claim 44, wherein the wafer holder comprises a rotating chuck.

46. The apparatus of claim 44, wherein the wafer holder comprises a cassette submerged in a cleaning tank.

47. The apparatus of claim 44, wherein the inlet comprises a nozzle.

48. The apparatus of claim 44, wherein the transducer is connected to the inlet and imparts acoustic energy to the liquid flowing through the inlet.

49. The apparatus of claim 44, wherein the first time period is determined as a time period that achieves the best cleaning effect on the features.

50. The apparatus of claim 44, wherein the second time period is determined as a time period that achieves the best cleaning effect on the features.

51. The apparatus of claim 44, wherein the first time period ends prior to at least one of the features being blocked by the bubbles.

52. The apparatus of claim 44, wherein the first time period ends after at least one of the features being blocked by the bubbles.

53. The apparatus of claim 44, wherein the second power level is lower than the first power level.

54. The apparatus of claim 53, wherein the second power level is zero.

55. The apparatus of claim 44, wherein the second frequency is higher than the first frequency.

56. The apparatus of claim 44, wherein acoustic energy in the second time period is in antiphase to acoustic energy in the first time period.

57. The apparatus of claim 44, wherein the first frequency is equal to the second frequency, while the first power level is higher than the second power level.

58. The apparatus of claim 44, wherein the first frequency is higher than the second frequency, while the first power level is higher than the second power level.

59. The apparatus of claim 44, wherein the first frequency is lower than the second frequency, while the first power level is equal to the second power level.

60. The apparatus of claim 44, wherein the first frequency is lower than the second frequency, while the first power level is higher than the second power level.

61. The apparatus of claim 44, wherein the first frequency is lower than the second frequency, while the first power lever is lower than the second power level.

62. The apparatus of claim 44, wherein the first power level rises during the first time period.

63. The apparatus of claim 44, wherein the first power level falls during the first time period.

64. The apparatus of claim 44, wherein the first power level both rises and falls during the first time period.

65. The apparatus of claim 44, wherein the first frequency changes from a higher value to a lower value during the first time period.

66. The apparatus of claim 44, wherein the first frequency changes from a lower value to a higher value during the first time period.

67. The apparatus of claim 44, wherein the first frequency changes from a lower value to a higher value and then back to the lower value during the first time period.

68. The apparatus of claim 44, wherein the first frequency changes from a higher value to a lower value and then back to the higher value during the first time period.

69. The apparatus of claim 44, wherein the first frequency is set as f_1 first, f_3 later and f_4 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

70. The apparatus of claim 44, wherein the first frequency is set as f_4 first, f_3 later and f_1 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

71. The apparatus of claim 44, wherein the first frequency is set as f_1 first, f_4 later and f_3 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

72. The apparatus of claim 44, wherein the first frequency is set as f_3 first, f_4 later and f_1 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

73. The apparatus of claim 44, wherein the first frequency is set as f_3 first, f_1 later and f_4 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

74. The apparatus of claim 44, wherein the first frequency is set as f_4 first, f_1 later and f_3 at last during the first time period, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

75. The apparatus of claim 44, wherein the second frequency is zero and the second power level remains a constant positive value during the second time period.

76. The apparatus of claim 44, wherein the second frequency is zero and the second power level remains a constant negative value during the second time period.

77. The apparatus of claim 44, wherein the features comprise vias or trenches having depth to width ratios of at least 3.

78. The apparatus of claim 44, wherein a device manufacturing node of the semiconductor wafer is no more than 16 nanometers.

79. The apparatus of claim 44, wherein the wafer holder is further configured to rotate the wafer with respect to the transducer as acoustic energy is delivered.

80. The apparatus of claim 44, wherein the second time period ends after a ratio of total bubble volume inside the features falls much lower than a cavitation saturation point.

81. The apparatus of claim 44, wherein the first time period ends before a ratio of total bubble volume inside the features reaches a cavitation saturation point.

82. The apparatus of claim 44, wherein the first time period ends when a ratio of total bubble volume inside the features reaches a cavitation saturation point.

83. The apparatus of claim 44, wherein a duration of the first time period is $m\tau_1$, where τ_1 is a time for a ratio of total bubble volume inside the features reaches a cavitation saturation point.

84. The apparatus of claim 83, wherein m is a value between 0.1 to 100.

85. The apparatus of claim 44, wherein temperatures inside the bubbles decrease in the second time period.

86. The apparatus of claim 85, wherein temperatures inside the bubble decrease to near a temperature of said liquid in the second time period.

87. The apparatus of claim 44, wherein the first time period is shorter than 2,000 times of a cycle period of the first frequency.

88. The apparatus of claim 44, wherein the first time period is shorter than $((V_i - V_0 - \Delta V)/(\Delta V - \delta V) + 1)/f_1$, where V_i is a desired volume, V_0 is an original volume, ΔV is a volume compression of the bubble after one time of compression, δV is a volume increase of the bubble after one time of expansion, and f1 is the first frequency.

89. A controller for a power supply of a transducer comprising a timer, the controller being configured to control the transducer based on the timer to:

deliver acoustic energy to liquid applied on a semiconductor wafer at a first frequency and a first power level for a predetermined first time period, wherein sizes of bubbles inside features of patterned structures of the semiconductor wafer increase during the first time period; and

deliver acoustic energy to the liquid at a second frequency and a second power level for a predetermined second time period, wherein sizes of bubbles inside features decrease during the second time period,

wherein the controller is configured to alternately apply the first and second time periods one after another for a predetermined number of cycles.

90. The controller of claim 89, wherein the first time period is determined as a time period that achieves the best cleaning effect on the features.

91. The controller of claim 89, wherein the second time period is determined as a time period that achieves the best cleaning effect on the features.

92. The controller of claim 89, wherein the first time period ends prior to at least one of the features being blocked by the bubbles.

93. The controller of claim 89, wherein the first time period ends after at least one of the features being blocked by the bubbles.

94. The controller of claim 89, wherein the second power level is lower than the first power level.

95. The controller of claim 94, wherein the second power level is zero.