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 bubble implosion occurs in 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 the first and second time periods are alternately applied one after another for a predetermined number of cycles,

wherein the first and second time periods, the first and second power levels, and the first and second frequencies are determined such that no feature is damaged as a result of delivering the acoustic energy.

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

3. The method of claim 2, wherein the second power level is zero.

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

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

6. 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.

7. 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.

8. 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.

9. 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.

10. 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.

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

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

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

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

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

16. 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.

17. 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.

18. 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.

19. 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.

20. 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.

21. 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.

22. 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.

23. 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.

24. 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.

25. 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.

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

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

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

29. The method of claim 1, wherein the bubble implosion is controlled under an implosion intensity that would result in damages to the patterned structures by controlling Tn below Td, wherein Tn is a maximum temperature of the bubbles after the predetermined number of cycles, and Td is a temperature of the bubbles that would result in implosion with a high intensity damaging the patterned structures.

30. The method of claim 1, wherein the features are not damaged by expansion of bubbles in the first time period.

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

32. The method of claim 31, wherein temperatures inside the bubble decrease to near a temperature of said liquid in the second time period.

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

34. The method of claim 1, wherein the first time period is shorter than $((T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1)/f_1$, where T_i is an implosion temperature, T_0 is a temperature of the liquid, ΔT is a temperature increase after one time of compression, δT is a temperature decrease after one time of expansion, and f1 is the first frequency.

35. 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 bubble implosion occurs in 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 the controller is configured to alternately apply the first and second time periods one after another for a predetermined number of cycles,

wherein the first and second time periods, the first and second power levels, and the first and second frequencies are determined such that no feature is damaged as a result of delivering the acoustic energy.

36. The apparatus of claim 35, wherein the wafer holder comprises a rotating chuck.

37. The apparatus of claim 35, wherein the wafer holder comprises a cassette submerged in a cleaning tank.

38. The apparatus of claim 35, wherein the inlet comprises a nozzle.

39. The apparatus of claim 35, wherein the transducer is connected to the inlet and imparts acoustic energy to the liquid flowing through the inlet.

40. The apparatus of claim 35, wherein the second power level is lower than the first power level.

41. The apparatus of claim 40, wherein the second power level is zero.

42. The apparatus of claim 35, wherein the second frequency is higher than the first frequency.

43. The apparatus of claim 35, wherein acoustic energy in the second time period is in antiphase to acoustic energy in the first time period.

44. The apparatus of claim 35, wherein the first frequency is equal to the second frequency, while the first power level is higher than the second power level.

45. The apparatus of claim 35, wherein the first frequency is higher than the second frequency, while the first power level is higher than the second power level.

46. The apparatus of claim 35, wherein the first frequency is lower than the second frequency, while the first power level is equal to the second power level.

47. The apparatus of claim 35, wherein the first frequency is lower than the second frequency, while the first power level is higher than the second power level.

48. The apparatus of claim 35, wherein the first frequency is lower than the second frequency, while the first power lever is lower than the second power level.

49. The apparatus of claim 35, wherein the first power level rises during the first time period.

50. The apparatus of claim 35, wherein the first power level falls during the first time period.

51. The apparatus of claim 35, wherein the first power level both rises and falls during the first time period.

52. The apparatus of claim 35, wherein the first frequency changes from a higher value to a lower value during the first time period.

53. The apparatus of claim 35, wherein the first frequency changes from a lower value to a higher value during the first time period.

54. The apparatus of claim 35, 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.

55. The apparatus of claim 35, 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.

56. The apparatus of claim 35, 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.

57. The apparatus of claim 35, 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.

58. The apparatus of claim 35, 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.

59. The apparatus of claim 35, 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.

60. The apparatus of claim 35, 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.

61. The apparatus of claim 35, 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.

62. The apparatus of claim 35, wherein the second frequency is zero and the second power level remains a constant positive value during the second time period.

63. The apparatus of claim 35, wherein the second frequency is zero and the second power level remains a constant negative value during the second time period.

64. The apparatus of claim 35, wherein the features comprise vias or trenches having depth to width ratios of at least 3.

65. The apparatus of claim 35, wherein a device manufacturing node of the semiconductor wafer is no more than 16 nanometers.

66. The apparatus of claim 35, wherein the wafer holder is further configured to rotate the wafer with respect to the transducer as acoustic energy is delivered.

67. The apparatus of claim 35, wherein the bubble implosion is controlled under an implosion intensity that would result in damages to the patterned structures by controlling Tn below Td, wherein Tn is a maximum temperature of the bubbles after the predetermined number of cycles, and Td is a temperature of the bubbles that would result in implosion with a high intensity damaging the patterned structures.

68. The apparatus of claim 35, wherein the features are not damaged by expansion of bubbles in the first time period.

69. The apparatus of claim 35, wherein temperatures inside bubbles decrease in the second time period.

70. The apparatus of claim 69, wherein temperatures inside the bubble decrease to near a temperature of said liquid in the second time period.

71. The apparatus of claim 35, wherein the first time period is shorter than 2,000 times of a cycle period of the first frequency.

72. The apparatus of claim 35, wherein the first time period is shorter than $((T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1)/f_1$, where T_i is an implosion temperature, T_0 is a temperature of the liquid, ΔT is a temperature

increase after one time of compression, δT is a temperature decrease after one time of expansion, and f1 is the first frequency.

73. 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 bubble implosion occurs in 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 the controller is configured to alternately apply the first and second time periods one after another for a predetermined number of cycles,

wherein the first and second time periods, the first and second power levels, and the first and second frequencies are determined such that no feature is damaged as a result of delivering the acoustic energy.

74. The controller of claim 73, wherein the second power level is lower than the first power level.

75. The controller of claim 74, wherein the second power level is zero.