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References

1. Gilmer, G.H. and M.H. Grabow, *MOLECULAR-DYNAMICS STUDIES OF CRYSTAL-GROWTH AND THIN-FILMS*. Acs Symposium Series, 1987. **353**: p. 218-236.
2. Cheung, J.T. and H. Sankur, *GROWTH OF THIN-FILMS BY LASER-INDUCED EVAPORATION*. Crc Critical Reviews in Solid State and Materials Sciences, 1988. **15**(1): p. 63-109.
3. Rao, U.V.S., J.S. Kumar, and K.N. Reddy, *NUCLEATION, GROWTH AND CHARACTERIZATION OF THIN SOLID FILMS*. Progress in Crystal Growth and Characterization of Materials, 1987. **15**(3-4): p. 187-314.
4. Romeo, N., *QUASI-RHEOTAXIAL GROWTH OF LARGE CRYSTALLINE GRAIN THIN-FILMS ON LOW-COST SUBSTRATES FOR PHOTOVOLTAIC APPLICATIONS*. Progress in Crystal Growth and Characterization of Materials, 1984. **9**(1-2): p. 169-183.
5. Joyce, B.A., *GROWTH AND STRUCTURE OF SEMICONDUCTING THIN-FILMS*. Reports on Progress in Physics, 1974. **37**(3): p. 363-&.
6. Corso, M., et al., *Boron nitride nanomesh*. Science, 2004. **303**(5655): p. 217-220.
7. Novoselov, K.S., et al., *Electric Field Effect in Atomically Thin Carbon Films*. Science, 2004. **306**(5696): p. 666-669.
8. Novoselov, K.S., et al., *Two-dimensional gas of massless Dirac fermions in graphene*. Nature, 2005. **438**(7065): p. 197-200.
9. Laskowski, R., P. Blaha, and K. Schwarz, *Bonding of hexagonal BN to transition metal surfaces: An ab initio density-functional theory study*. Physical Review B, 2008. **78**(4): p. -.
10. Laskowski, R. and P. Blaha, *Unraveling the structure of the h-BN/Rh(111) nanomesh with ab initio calculations*. Journal of Physics-Condensed Matter, 2008. **20**(6): p. 064207.
11. Laskowski, R., et al., *Single-layer model of the hexagonal boron nitride nanomesh on the rh(111) surface*. Physical Review Letters, 2007. **98**(10): p. 106802.
12. Bunk, O., et al., *Surface X-ray diffraction study of boron-nitride nanomesh in air*. Surface Science, 2007. **601**(2): p. L7-L10.
13. Martocchia, D., et al., *h-BN on Rh(111): Persistence of a commensurate 13-on-12 superstructure up to high temperatures*. Surface Science, 2010. **604**(5-6): p. L9-L11.

References

14. Berner, S., et al., *Boron nitride nanomesh: Functionality from a corrugated monolayer*. *Angewandte Chemie-International Edition*, 2007. **46**(27): p. 5115-5119.
15. Müller, F., S. Hübner, and H. Sachdev, *Epitaxial growth of boron nitride on a Rh(111) multilayer system: Formation and fine tuning of a BN-nanomesh*. *Surface Science*, 2009. **603**(3): p. 425-432.
16. Goriachko, A., Y.B. He, and H. Over, *Complex growth of NanoAu on BN nanomeshes supported by Ru(0001)*. *Journal of Physical Chemistry C*, 2008. **112**(22): p. 8147-8152.
17. Goriachko, A. and H. Over, *Modern Nanotemplates Based on Graphene and Single Layer h-BN*. *Zeitschrift Fur Physikalische Chemie-International Journal of Research in Physical Chemistry & Chemical Physics*, 2009. **223**(1-2): p. 157-168.
18. Dil, H., et al., *Surface trapping of atoms and molecules with dipole rings*. *Science*, 2008. **319**(5871): p. 1824-1826.
19. Widmer, R., et al., *Electrolytic in situ STM investigation of h-BN-nanomesh*. *Electrochemistry Communications*, 2007. **9**(10): p. 2484-2488.
20. Dong, G.C., et al., *How Boron Nitride Forms a Regular Nanomesh on Rh(111)*. *Physical Review Letters*, 2010. **104**(9): p. 096102.
21. Preobrajenski, A.B., et al., *Monolayer h-BN on lattice-mismatched metal surfaces: On the formation of the nanomesh*. *Chemical Physics Letters*, 2007. **446**(1-3): p. 119-123.
22. Goriachko, A., et al., *Self-assembly of a hexagonal boron nitride nanomesh on Ru(0001)*. *Langmuir*, 2007. **23**(6): p. 2928-2931.
23. Morscher, M., et al., *Formation of single layer h-BN on Pd(111)*. *Surface Science*, 2006. **600**(16): p. 3280-3284.
24. Auwarter, W., et al., *Defect lines and two-domain structure of hexagonal boron nitride films on Ni(111)*. *Surface Science*, 2003. **545**(1-2): p. L735-L740.
25. Oshima, C., et al., *A heteroepitaxial multi-atomic-layer system of graphene and h-BN*. *Surface Review and Letters*, 2000. **7**(5-6): p. 521-525.
26. Oshima, C., et al., *A hetero-epitaxial-double-atomic-layer system of monolayer graphene/monolayer h-BN on Ni(111)*. *Solid State Communications*, 2000. **116**(1): p. 37-40.
27. Oshima, C., et al., *Hetero-epitaxial double-atomic-layer system of monolayer graphene monolayer h-BN on Ni(111) studied by HREELS*. *Microbeam Analysis 2000, Proceedings*, 2000(165): p. 313-314.
28. Paffett, M.T., et al., *Borazine adsorption and decomposition at Pt(111) and Ru(001) surfaces*. *Surface Science*, 1990. **232**(3): p. 286-296.
29. Čavar, E., et al., *A single h-BN layer on Pt(111)*. *Surface Science*, 2008. **602**(9): p. 1722-1726.

30. Preobrajenski, A.B., et al., *Influence of chemical interaction at the lattice-mismatched h-BN/Rh (111) and h-BN/Pt (111) interfaces on the overlayer morphology*. Physical Review B, 2007. **75**(24): p. 245412.
31. Martocchia, D., et al., *h-BN/Ru(0001) nanomesh: A 14-on-13 superstructure with 3.5 nm periodicity*. Surface Science, 2010. **604**(5-6): p. L16-L19.
32. Goriachko, A., A.A. Zakharov, and H. Over, *Oxygen-etching of h-BN/Ru(0001) nanomesh on the nano- and mesoscopic scale*. Journal of Physical Chemistry C, 2008. **112**(28): p. 10423-10427.
33. Hoogeman, M.S., et al., *Design and performance of a programmable-temperature scanning tunneling microscope*. Review of Scientific Instruments, 1998. **69**(5): p. 2072-2080.
34. Rost, M.J., et al., *Scanning probe microscopes go video rate and beyond*. Review of Scientific Instruments, 2005. **76**(5): p. 053710.
35. Castro Neto, A.H., et al., *The electronic properties of graphene*. Reviews of Modern Physics, 2009. **81**(1): p. 109-162.
36. Westervelt, R.M., *Applied physics - Graphene nanoelectronics*. Science, 2008. **320**(5874): p. 324-325.
37. Ponomarenko, L.A., et al., *Chaotic Dirac Billiard in Graphene Quantum Dots*. Science, 2008. **320**(5874): p. 356-358.
38. Geim, A.K. and K.S. Novoselov, *The rise of graphene*. Nature Materials, 2007. **6**(3): p. 183-191.
39. Zhang, Y., et al., *Experimental observation of the quantum Hall effect and Berry's phase in graphene*. Nature, 2005. **438**(7065): p. 201-204.
40. Charlier, J.-C., X. Blase, and S. Roche, *Electronic and transport properties of nanotubes*. Reviews of Modern Physics, 2007. **79**(2): p. 677.
41. Wallace, P.R., *The Band Theory of Graphite*. Physical Review, 1947. **71**(9): p. 622.
42. McClure, J.W., *Diamagnetism of Graphite*. Physical Review, 1956. **104**(3): p. 666.
43. Du, X., et al., *Fractional quantum Hall effect and insulating phase of Dirac electrons in graphene*. Nature, 2009. **462**(08522): p. 192-195.
44. Novoselov, K.S., et al., *Room-Temperature Quantum Hall Effect in Graphene*, 2007. p. 1379-.
45. Calogeracos, A. and N. Dombey, *History and physics of the Klein paradox*, 1999, Taylor & Francis. p. 313 - 321.
46. Schmid, M., et al., *Nanotemplate with holes: Ultrathin alumina on Ni₃Al(111)*. Physical Review Letters, 2007. **99**(19): p. -.
47. Lui, C.H., et al., *Ultraflat graphene*. Nature, 2009. **462**(7271): p. 339-341.

References

48. Emtsev, K.V., et al., *Towards wafer-size graphene layers by atmospheric pressure graphitization of silicon carbide*. Nature Materials, 2009. **8**(3): p. 203-207.
49. Hass, J., et al., *Highly ordered graphene for two dimensional electronics*, in *Appl. Phys. Lett* 2006, AIP. p. 143106.
50. Berger, C., et al., *Electronic Confinement and Coherence in Patterned Epitaxial Graphene*. Science, 2006. **312**(5777): p. 1191-1196.
51. Loginova, E., et al., *Factors influencing graphene growth on metal surfaces*. New Journal of Physics, 2009. **11**: p. 063046.
52. Martoccia, D., et al., *Graphene on Ru(0001): A 25x25 supercell*. Physical Review Letters, 2008. **101**(12): p. 126102.
53. McCarty, K.F., et al., *Kinetics and thermodynamics of carbon segregation and graphene growth on Ru(0001)*. Carbon, 2009. **47**(7): p. 1806-1813.
54. Coraux, J., et al., *Structural coherency of graphene on Ir(111)*. Nano Letters, 2008. **8**(2): p. 565-570.
55. Oshima, C. and A. Nagashima, *Ultra-thin epitaxial films of graphite and hexagonal boron nitride on solid surfaces*. Journal of Physics-Condensed Matter, 1997. **9**(1): p. 1-20.
56. Kim, K.S., et al., *Large-scale pattern growth of graphene films for stretchable transparent electrodes*. Nature, 2009. **457**(7230): p. 706-710.
57. Sutter, P.W., J.I. Flege, and E.A. Sutter, *Epitaxial graphene on ruthenium*. Nature Materials, 2008. **7**(5): p. 406-411.
58. Wintterlin, J. and M.L. Bocquet, *Graphene on metal surfaces*. Surface Science, 2009. **603**(10-12): p. 1841-1852.
59. Isett, L.C. and J.M. Blakely, *Segregation Isosteres for Carbon at (100) Surface of Nickel*. Surface Science, 1976. **58**(2): p. 397-414.
60. Yu, Q.K., et al., *Graphene segregated on Ni surfaces and transferred to insulators*. Applied Physics Letters, 2008. **93**(11): p. 113103.
61. Castner, D.G., B.A. Sexton, and G.A. Somorjai, *Leed and Thermal Desorption Studies of Small Molecules (H₂, O₂, Co, Co₂, No, C₂h₄, C₂h₂ and C) Chemisorbed on Rhodium (111) and (100) Surfaces*. Surface Science, 1978. **71**(3): p. 519-540.
62. Shelton, J.C., H.R. Patil, and J.M. Blakely, *Equilibrium Segregation of Carbon to a Nickel (111) Surface - Surface Phase-Transition*. Surface Science, 1974. **43**(2): p. 493-520.
63. Bertoni, G., et al., *First-principles calculation of the electronic structure and EELS spectra at the graphene/Ni(111) interface*. Physical Review B, 2005. **71**(7): p. 075402.

64. Karpan, V.M., et al., *Theoretical prediction of perfect spin filtering at interfaces between close-packed surfaces of Ni or Co and graphite or graphene*. Physical Review B, 2008. **78**(19): p. 195419.
65. Sutter, P., *EPITAXIAL GRAPHENE How silicon leaves the scene*. Nature Materials, 2009. **8**(3): p. 171-172.
66. Reina, A., et al., *Large Area, Few-Layer Graphene Films on Arbitrary Substrates by Chemical Vapor Deposition*. Nano Letters, 2009. **9**(1): p. 30-35.
67. Li, X., et al., *Large-Area Graphene Single Crystals Grown by Low-Pressure Chemical Vapor Deposition of Methane on Copper*. Journal of the American Chemical Society, 2011. **133**(9): p. 2816-2819.
68. Liu, W., et al., *Synthesis of high-quality monolayer and bilayer graphene on copper using chemical vapor deposition*. Carbon, 2011. **49**(13): p. 4122-4130.
69. Li, X.S., et al., *Large-Area Synthesis of High-Quality and Uniform Graphene Films on Copper Foils*. Science, 2009. **324**(5932): p. 1312-1314.
70. Bae, S., et al., *Roll-to-roll production of 30-inch graphene films for transparent electrodes*. Nat Nano, 2010. **5**(8): p. 574-578.
71. Yu, Q., et al., *Control and characterization of individual grains and grain boundaries in graphene grown by chemical vapour deposition*. Nature Materials, 2011. **10**(6): p. 443-449.
72. Chen, J.G., et al., *Controlling surface reactivities of transition metals by carbide formation*. Journal of Molecular Catalysis a-Chemical, 1998. **131**(1-3): p. 285-299.
73. Delouise, L.A. and N. Winograd, *Carbon-Monoxide Adsorption and Desorption on Rh(111) and Rh(331) Surfaces*. Surface Science, 1984. **138**(2-3): p. 417-431.
74. Rogers, G.L., *A Simple Method of Calculating Moiré Patterns*. Proc. Phys. Soc, 1959. **73**: p. 142-144.
75. Lee, K.H., et al., *Large-Scale Synthesis of High-Quality Hexagonal Boron Nitride Nanosheets for Large-Area Graphene Electronics*. Nano Letters, 2012. **12**(2): p. 714-718.
76. Giovannetti, G., et al., *Substrate-induced band gap in graphene on hexagonal boron nitride: Ab initio density functional calculations*. Physical Review B, 2007. **76**(7): p. 073103.
77. Ramasubramaniam, A., D. Naveh, and E. Towe, *Tunable Band Gaps in Bilayer Graphene–BN Heterostructures*. Nano Letters, 2011. **11**(3): p. 1070-1075.
78. Britnell, L., et al., *Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures*. Science, 2012. **335**(6071): p. 947-950.
79. <http://link.aps.org/supplemental/10.1103/PhysRevLett.104.096102>.
80. Zhang, Z.Y. and M.G. Lagally, *Atomistic processes in the early stages of thin-film growth*. Science, 1997. **276**(5311): p. 377-383.

References

81. Venables, J.A., *Introduction to Surface and Thin Film Processes* 2000, Cambridge: Cambridge University press.
82. Turnbull, D. and R.E. Hoffman, *The effect of relative crystal and boundary orientations on grain boundary diffusion rates*. *Acta Metallurgica*, 1954. **2**(3): p. 419-426.
83. Couling, S.R.L. and R. Smoluchowski, *ANISOTROPY OF DIFFUSION IN GRAIN BOUNDARIES*. *Journal of Applied Physics*, 1954. **25**(12): p. 1538-1542.
84. Venables, J.A., *Introduction to Surface and Thin Film Processes* 2001, Cambridge: Cambridge University press.
85. Guo, H.L., et al., *A Green Approach to the Synthesis of Graphene Nanosheets*. *ACS Nano*, 2009. **3**(9): p. 2653-2659.
86. Dubois, L.H., D.G. Castner, and G.A. Somorjai, *The Chemisorption of Acetylene and Ethylene on Rh(111) - a Low-Energy Electron-Diffraction (Leed), High-Resolution Electron-Energy Loss (Els), and Thermal-Desorption Mass-Spectrometry (Tds) Study*. *Journal of Chemical Physics*, 1980. **72**(9): p. 5234-5240.
87. Ibach, H., *Physics of Surfaces and Interfaces*. Vol. 10. 2006, Jülich: Springer-Verlag Berlin Heidelberg. 525.
88. Rut'kov, E.V., A.V. Kuz'michev, and N.R. Gall, *Carbon interaction with rhodium surface: Adsorption, dissolution, segregation, growth of graphene layers*. *Physics of the Solid State*, 2011. **53**(5): p. 1092-1098.
89. Wang, B., et al., *Coupling Epitaxy, Chemical Bonding, and Work Function at the Local Scale in Transition Metal-Supported Graphene*. *ACS Nano*, 2010. **4**(10): p. 5773-5782.
90. Sinharoy, S. and L.L. Levenson, *The formation and decomposition of nickel carbide in evaporated nickel films on graphite*. *Thin Solid Films*, 1978. **53**(1): p. 31-36.
91. Röhrl, J., et al., *Raman spectra of epitaxial graphene on SiC(0001)*. *Applied Physics Letters*, 2008. **92**(20): p. 201918.
92. Zakharchenko, K.V., M.I. Katsnelson, and A. Fasolino, *Finite Temperature Lattice Properties of Graphene beyond the Quasiharmonic Approximation*. *Physical Review Letters*, 2009. **102**(4): p. 046808.
93. van Gastel, R., et al., *Selecting a single orientation for millimeter sized graphene sheets*. *Applied Physics Letters*, 2009. **95**(12): p. 121901.
94. Starodub, E., et al., *Graphene growth by metal etching on Ru(0001)*. *Physical Review B*, 2009. **80**(23): p. 235422.
95. Bertel, E., G. Rosina, and F.P. Netzer, *The structure of benzene on Rh(111): Coadsorption with CO*. *Surface Science Letters*, 1986. **172**(1): p. L515-L522.

-
96. Sellidj, A. and B.E. Koel, *Vibrational and electronic properties of monolayer and multilayer fullerene C60 films on rhodium (111)*. The Journal of Physical Chemistry, 1993. **97**(39): p. 10076-10082.
 97. Pitarke, J.M., P.M. Echenique, and F. Flores, *Apparent Barrier Height for Tunneling Electrons in Stm*. Surface Science, 1989. **217**(1-2): p. 267-275.
 98. Loginova, E., et al., *Evidence for graphene growth by C cluster attachment*. New Journal of Physics, 2008. **10**: p. 093026.
 99. Dong, G., *Graphene formation on metal surfaces investigated by in-situ STM*. New Journal of Physics, 2012.
 100. <http://iopscience.iop.org/1367-2630/14/5/053033/media>.
 101. Dong, G.C., et al., *Graphene formation on metal surfaces investigated by in-situ scanning tunneling microscopy*. New Journal of Physics, 2012. **14**(5): p. 053033.
 102. Wu, P., et al., *Lattice Mismatch Induced Nonlinear Growth of Graphene*. Journal of the American Chemical Society, 2012. **134**(13): p. 6045-6051.
 103. Wang, B., et al., *Size-Selective Carbon Nanoclusters as Precursors to the Growth of Epitaxial Graphene*. Nano Letters, 2011. **11**(2): p. 424-430.
 104. Luo, Z., et al., *Growth Mechanism of Hexagonal-Shape Graphene Flakes with Zigzag Edges*. ACS Nano, 2011. **5**(11): p. 9154-9160.
 105. Lahiri, J., et al., *Graphene Growth on Ni(111) by Transformation of a Surface Carbide*. Nano Letters, 2011. **11**(2): p. 518-522.