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Ultrafast and nanoscale diodes

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Charge carrier transport across interfaces of dissimilar materials (including vacuum) is the essence of all electronic devices. Ultrafast charge transport across a nanometre length scale is of fundamental importance in the miniaturization of vacuum and plasma electronics. With the combination of recent advances in electronics, photonics and nanotechnology, these miniature devices may integrate with solid-state platforms, achieving superior performance. This paper reviews recent modelling efforts on quantum tunnelling, ultrafast electron emission and transport, and electrical contact resistance. Unsolved problems and challenges in these areas are addressed.

Key words: plasma devices, strongly coupled plasmas

1. Introduction

Diodes, or more generally charge transport phenomena, are central to high power microwave sources, vacuum microelectronics, electron and ion sources, and high current drivers used in high-energy density physics experiments. One of the great challenges in these areas is the miniaturization of vacuum and plasma electronic devices. With the combination of recent advances in electronics, photonics and nanotechnology, these miniature devices may integrate with solid-state platforms, thus forming highly compact systems with high power handling capability. Applications in ultrafast electron sources, accelerators, and radiation sources, ranging from millimetre wave to X-rays are envisioned (Booske 2008; Barletta *et al.* 2010; Booske *et al.* 2011; Peralta *et al.* 2013; England *et al.* 2014; Hommelhoff & Kling 2014; Armstrong 2015).

Since the pioneering work of Spindt (Spindt 1968; Spindt *et al.* 1976) on the fabrication of cathodes using microfabrication technologies, extensive efforts have been made to scale down vacuum electronic devices to the microscale or even nanoscale. Recently, nanoscale vacuum gap has been used as the conducting channel in nanoelectronics (Srisonphan, Jung & Kim 2012; Stoner & Glass 2012; Han & Meyyappan 2014; Wu *et al.* 2016). Because of ballistic transport, vacuum is intrinsically a better carrier transport medium compared to a solid, in which the carriers suffer from optical and acoustic phonon scattering, resulting in local heating and degradation in both signal quality and the device itself. The vacuum-solid-state

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integrated nanodevices thus combine the advantages of ballistic transport through vacuum with the scalability, low cost and reliability of conventional silicon transistor technology.

This paper highlights some recent modelling efforts in the development of ultrafast and nanoscale diodes, including quantum tunnelling current, ultrafast electron emission, and issues in current crowding and contact resistance. Unsolved problems and challenges in these areas are addressed.

2. Quantum tunnelling current

Tunnelling effects in nanoscale metal-insulator (including vacuum)-metal (MIM) junctions were studied extensively by Simmons in the 1960s (Simmons 1963*a*,*b*). Simmons' formulas were derived by considering only the emission process from the electrodes, where the effects of image charge are considered, but the electron space charge potential and the electron exchange-correlation potential inside the insulator thin films are generally ignored. An excellent review on the tunnelling current in MIM structures is given in Kao (2004). The effects of space charge in a vacuum nanogap have subsequently been studied theoretically (Lau *et al.* 1991; Ang, Kwan & Lau 2003; Ang & Zhang 2007) and experimentally (Bhattacharjee, Vartak & Mukherjee 2008; Bhattacharjee & Chowdhury 2009).

Recently, a general scaling law for the quantum tunnelling current in nano- and sub-nanoscale MIM diodes has been developed by self-consistently solving the coupled Schrödinger and Poisson equations (Zhang 2015). It includes the effects of space charge and exchange-correlation potential, as well as current emission from the anode. As shown in figure 1, the self-consistent model recovers various scaling laws in limiting cases: Simmons's formula (Simmons 1963*a*) in the direct tunnelling regime, the Fowler–Nordheim law (Fowler & Nordheim 1928) in the field emission regime, and the quantum Child–Langmuir law (Lau *et al.* 1991; Ang *et al.* 2003) in the space charge limited (SCL) regime. Note that in the SCL regime, the self-consistent current approaches the quantum version of the Child–Langmuir law, which exceeds the classical Child–Langmuir law (Child 1911; Langmuir 1913) because of quantum tunnelling. Smooth transition between various regimes has been demonstrated.

The proposed model may be applied to broad areas involving tunnelling junctions, for example, quantum plasmonics (Esteban *et al.* 2012; Savage *et al.* 2012), transition voltage spectroscopy (Trouwborst *et al.* 2011; Bâldea 2012; Sotthewes *et al.* 2014), molecular electronics (Bâldea & Köppel 2012; Tan *et al.* 2014), and resistive switching (Ziegler, Harnack & Kohlstedt 2014).

Further studies on quantum tunnelling current may include: (i) examination of the Wentzel–Kramers–Brillouin–Jeffreys (WKBJ) approximation and the free electron gas model assumed for the electrodes against exact first principle calculations (Zhang, Lu & Pantelides 2006; Yaghoobi, Walus & Nojeh 2009); (ii) the effects of electrode geometry (Luginsland, Lau & Gilgenbach 1996; Lau 2001; Luginsland *et al.* 2002; Rokhlenko & Lebowitz 2003; Shiffler *et al.* 2005; Jensen 2010; Tang *et al.* 2012; Fairchild *et al.* 2015; Harris *et al.* 2015; Jensen *et al.* 2015); (iii) comparison of the classical image charge potential with that of quantum theory (Newns 1969; Koh & Ang 2008; Myöhänen *et al.* 2012); (iv) the nature of the ion lattice of the electrodes (Spindt *et al.* 1976); (v) dissimilar electrode materials (Simmons 1963*b*); (vi) possible charge trapping inside the insulator film (Rose 1955; Kao 2004); (vii) ac bias and time/frequency dependence (Valfells *et al.* 2002; Feng & Verboncoeur 2005, 2006, 2008; Pedersen, Manolescu and Valfells 2010; Caflisch & Rosin 2012;

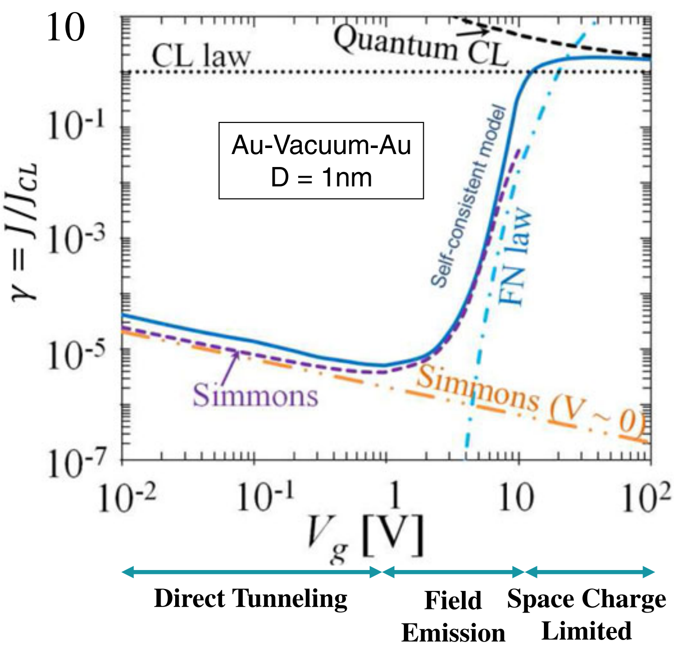

FIGURE 1. Self-consistent model for the quantum tunnelling current in a one-dimensional planar nanoscale Au-vaccum-Au diode (Zhang 2015). The gap distance is $D = 1$ nm, gap voltage is V_g and the normalized current density $\gamma = J/J_{CL}$ is in terms of the Child–Langmuir law J_{CL}. The J-V (current density–voltage) curve is compared with scaling laws in various limits: Simmons formula (Simmons 1963*a*), Fowler–Nordheim (FN) law (Fowler & Nordheim 1928), Child–Langmuir (CL) law (Child 1911; Langmuir 1913) and quantum CL law (Lau *et al.* 1991; Ang *et al.* 2003).

Cocker *et al.* 2013; Griswold, Fisch & Wurtele 2012; Rokhlenko 2015; Liu *et al.* 2015*a*,*b*; Griswold & Fisch 2016); and (viii) comparison of theory and modelling with experiments (Spindt *et al.* 1976; Das & Jagadeesh 1981; Teague 1986; Cahay *et al.* 1987; Bhattacharjee *et al.* 2008; Bhattacharjee & Chowdhury 2009; Bormann *et al.* 2010; Cocker *et al.* 2013; Tan *et al.* 2014). These studies are important to vacuum nanoelectronics, including gated vacuum nanodevices (Han, Oh & Meyyappan 2012), transition voltage spectroscopy in vacuum diodes (Bâldea 2014) and non-equilibrium vacuum tunnelling junctions (Maksymovych 2013).

3. Ultrafast electron emission

Laser-driven ultrafast electron emission offers the possibility of manipulation and control of coherent electron dynamics in ultrashort spatio-temporal scales (Hommelhoff & Kling 2014). Production of ultrashort electron bunches provides the enabling technology for four-dimensional (4-D) time-resolved electron microscopy (Tao *et al.* 2012; Portman *et al.* 2013). It is also important to free electron lasers, laser acceleration of relativistic electrons, and ultrafast electron diffraction (Hommelhoff, Kealhofer & Kasevich 2006; Ropers *et al.* 2007). Perturbative theory to model laser-driven ultrafast electron emission was usually done with the strong field approximation (Bormann *et al.* 2010). Existing Floquet models for electron emission include only a laser wave field with zero direct current (dc) bias (Yalunin, Gulde & Ropers 2011).

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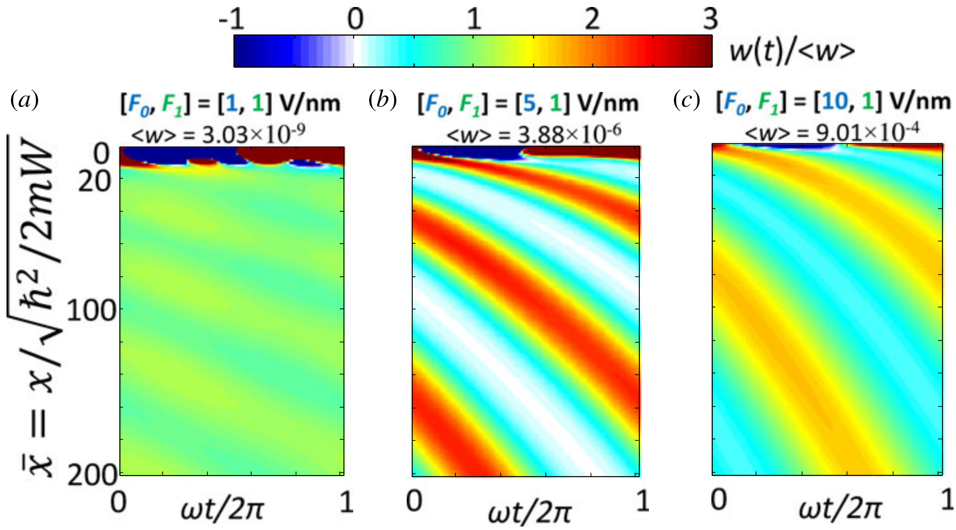

FIGURE 2. Time-dependent total emission current density w (x, t) normalized to the time-averaged emission current density $<w>$, as a function of time t and space x, for laser electric field $F_1 = 1$ V nm^{-1} under three dc fields $F_0 = 1$, 5, 10 V nm^{-1} (Zhang & Lau 2016). Time is normalized to the laser period $2\pi/\omega$, and space is normalized to a length scale $\sqrt{\hbar^2/2mW}$, where ω is the laser frequency, m is the electron rest mass and W is the metal work function. We assumed the metal is gold, with $W = 5.1$ eV, Fermi level $E_F = 5.53$ eV and laser wavelength $\lambda = 800$ nm. The vacuum–metal interface is located at $x = 0$.

We constructed an analytic solution for the highly nonlinear electron emission from a metal surface that is exposed to both a dc biased electric field and a single frequency laser electric field (Zhang & Lau 2016). By solving the time-dependent Schrödinger equation exactly, our theory is valid for arbitrary laser frequency and metal properties (work function and Fermi level). Various emission mechanisms, including multiphoton absorption or emission, optical or dc field emission, single-photon induced over-barrier emission, and various combinations of these, are all included in a single formulation. The time-dependent emission current reveals that intense current modulation may be possible even with a low intensity laser, by only increasing the applied dc bias, as shown in figure 2. A slowly varying envelope approximation has extended the results to pulsed excitation (Zhang & Lau 2016).

Future studies on ultrafast electron emission may include emission delay and scattered electron contributions, charge redistribution and thermalization (Pant & Ang 2013), field enhancement (Feng & Verboncoeur 2005, 2006, 2008; Miller, Lau & Booske 2007; Feng, Verboncoeur & Lin 2008; Jensen *et al.* 2008; Tang, Shiffler & Cartwright 2011) and space charge effects (Griswold, Fisch & Wurtele 2010; Pedersen *et al.* 2010; Caflisch & Rosin 2012; Griswold *et al.* 2012; Ilkov *et al.* 2015; Rokhlenko 2015; Liu *et al.* 2015*a*,*b*; Griswold & Fisch 2016), all under ultrafast conditions. It is important to link ultrafast strong-field laser physics in atoms and gaseous media to that in nanoclusters, solid-state surfaces and nanostructures (Corkum *et al.* 1988; Corkum 1993; Corkum, Burnett & Ivanov 1994; Rundquist *et al.* 1998; Corkum & Krausz 2007; Fan *et al.* 2015; Chen *et al.* 2016; Tao *et al.* 2016). These studies would offer unprecedented scientific advances in attosecond science (Corkum & Krausz 2007; Hommelhoff & Kling 2014; Tao *et al.* 2016).

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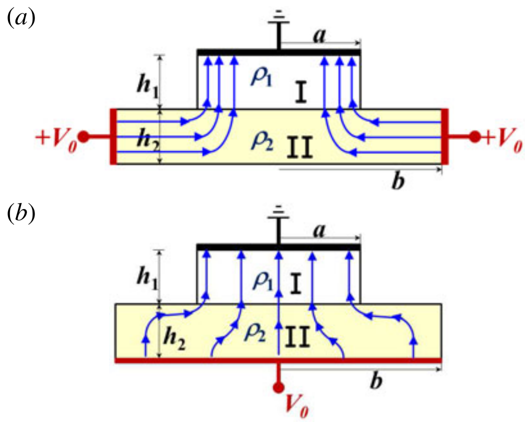

FIGURE 3. Two basic types of thin film contact: (*a*) the horizontal type (Zhang *et al.* 2011, 2012, 2013; Zhang & Lau 2014) and (*b*) the vertical type (Zhang & Lau 2013).

4. Current crowding and contact resistance

Contact resistance and current crowding are very important to plasma and vacuum electronics, such as wire array *z*-pinches (Gomez *et al.* 2008; Zier *et al.* 2008), field emitters (Shiffler *et al.* 2005; Park *et al.* 2006; Vlahos, Booske & Morgan 2007) and high power microwave devices (Booske 2008; Benford, Swegle & Schamiloglu 2015). In these systems, poor electrical contact prevents efficient power coupling to the load, produces unwanted plasma and even damages the electrodes. Contact resistance is also extremely important in wafer evaluation (Carbonero, Morin & Cabon 1995), thin film resistors (Hall 1968) and metal-oxide–vacuum junctions (Latham 1995). It is critical to semiconductor material and device characterization (Berger 1972; Schroder 1998). Contact resistance is one of the major limiting factors to devices made of exceptional materials, such as carbon nanotubes (CNTs), graphene and diamond (Li, Thostenson & Chou 2007; Grotjohn *et al.* 2014; Nouchi & Tanigaki 2014).

The fundamental model of electrical contact, Holm's *a*-spot theory (Holm 1967; Schroder 1998; Timsit 1999; Chin, Barber & Hu 2006), is generalized to include the effects of dissimilar materials and higher dimensions (Gomez *et al.* 2009; Lau & Tang 2009; Zhang & Lau 2010; Zhang 2012). By using Fourier series analysis, we derived new, simple analytical scaling laws for the total resistance for arbitrary values of dimensions and resistivities, for both Cartesian and cylindrical geometries (Zhang & Lau 2010). The models are extended to thin film contacts for two basic configurations: the horizontal type (figure 3*a*) (Zhang, Lau & Gilgenbach 2011; Zhang, Lau & Timsit 2012; Zhang, Hung & Lau 2013; Zhang & Lau 2014) and the vertical type (figure 3*b*) (Zhang & Lau 2013). Current crowding is systematically studied by calculating the current flow patterns (Zhang, Lau & Gilgenbach 2015*a*). The exact field solution accounts for both interface resistance and spreading resistance. It was recently applied to study current crowding and constriction resistance in electrically pumped nanolasers, where the effects of sidewall tilt were analysed (Zhang *et al.* 2016).

When electrical contacts are formed in micro- or nanoscale, the electron mean free path *l* may exceed the contact size *a*, so that electrons transport ballistically through the contact constriction (Sharvin 1965; Landauer 1996; Zhang & Hung 2014). If the system size is further reduced to be of the order of the Fermi wavelength, wave character features would be pronounced, where the quantization of ballistic electron transport through a constriction represents conduction as transmission. There are existing models of electrical contacts in ballistic (Sharvin 1965; Büttiker 1988; Datta & Anantram 1992; Landauer 1996) and quantum regimes (Mortensen *et al.* 1999; Datta 2005; Grosse *et al.* 2011; Solomon 2011; Xia *et al.* 2011). However, the transition between the classical, ballistic and quantum regimes remains unclear, and it requires further investigation. The underlying physics in these regimes is critical to the design and performance of the multitude of new devices that are expected to be developed in the near future.

5. Concluding remarks

Ultrafast and nanoscale diodes are essential components in the miniaturization of plasma and vacuum electronics, as recognized in a recent white paper for the US Department of Energy (Zhang *et al.* 2015*b*). Here, we review recent modelling efforts on three aspects of nanoscale diodes, quantum tunnelling, ultrafast electron emission and electrical contact. Unsolved problems and challenges in these areas are addressed.

The research outlined above is pushing the traditional boundary of plasma science and engineering, into neighbouring fields of nanoelectronics, ultrafast physics and material science. The applications of these research are immense, including single-molecule sensing, transition voltage spectroscopy, molecule electronics, resistive switching, CNT-, graphene- and diamond-based electronics, novel high brightness electron sources, ultrafast electron microscopes, variable stoichiometry photoemissive materials for detectors and sources, and novel compact particle accelerators.

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REFERENCES

ANG, L. K., KWAN, T. J. T. & LAU, Y. Y. 2003 New scaling of Child–Langmuir law in the quantum regime. *Phys. Rev. Lett.* **91** (20), 208303.

ANG, L. K. & ZHANG, P. 2007 Ultrashort-pulse Child–Langmuir law in the quantum and relativistic regimes. *Phys. Rev. Lett.* **98** (16), 164802.

ARMSTRONG, C. M. 2015 *The quest for the ultimate vacuum tube. In IEEE Spectrum: Technology, Engineering, and Science News 24 November 2015*, http://spectrum.ieee.org/semiconductors/devices/the-quest-for-the-ultimate-vacuum-tube.

BÂLDEA, I. 2012 Transition voltage spectroscopy in vacuum break junction: possible role of surface states. *Europhys. Lett.* **98** (1), 17010.

BÂLDEA, I. 2014 Concurrent conductance and transition voltage spectroscopy study of scanning tunneling microscopy vacuum junctions. Does it unravel new physics? *RSC Advances* **4** (63), 33257–33261.

BÂLDEA, I. & KÖPPEL, H. 2012 Evidence on single-molecule transport in electrostatically-gated molecular transistors. *Phys. Lett.* A **376** (17), 1472–1476.

BARLETTA, W. A., BISOGNANO, J., CORLETT, J. N., EMMA, P., HUANG, Z., KIM, K.-J., LINDBERG, R., MURPHY, J. B., NEIL, G. R., NGUYEN, D. C. *et al.* 2010 Free electron lasers: present status and future challenges. *Nucl. Instrum. Meth.* A **618** (1–3), 69–96.

BENFORD, J., SWEGLE, J. A. & SCHAMILOGLU, E. 2015 *High Power Microwaves*, 3rd edn. CRC Press.

BERGER, H. H. 1972 Models for contacts to planar devices. *Solid-State Electron.* **15** (2), 145–158.

BHATTACHARJEE, S. & CHOWDHURY, T. 2009 Experimental investigation of transition from Fowler–Nordheim field emission to space-charge-limited flows in a nanogap. *Appl. Phys. Lett.* **95** (6), 61501.

BHATTACHARJEE, S., VARTAK, A. & MUKHERJEE, V. 2008 Experimental study of space-charge-limited flows in a nanogap. *Appl. Phys. Lett.* **92** (19), 191503.

BOOSKE, J. H. 2008 Plasma physics and related challenges of millimeter-wave-to-terahertz and high power microwave generationa. *Phys. Plasmas* **15** (5), 55502.

BOOSKE, J. H., DOBBS, R. J., JOYE, C. D., KORY, C. L., NEIL, G. R., PARK, G.-S., PARK, J. & TEMKIN, R. J. 2011 Vacuum electronic high power terahertz sources. *IEEE Trans. Terahertz Sci. Technol.* **1** (1), 54–75.

BORMANN, R., GULDE, M., WEISMANN, A., YALUNIN, S. V. & ROPERS, C. 2010 Tip-enhanced strong-field photoemission. *Phys. Rev. Lett.* **105** (14), 147601.

BÜTTIKER, M. 1988 Symmetry of electrical conduction. *IBM J. Res. Dev.* **32** (3), 317–334.

CAFLISCH, R. E. & ROSIN, M. S. 2012 Beyond the Child–Langmuir limit. *Phys. Rev.* E **85** (5), 56408.

CAHAY, M., MCLENNAN, M., DATTA, S. & LUNDSTROM, M. S. 1987 Importance of space-charge effects in resonant tunneling devices. *Appl. Phys. Lett.* **50** (10), 612–614.

CARBONERO, J. L., MORIN, G. & CABON, B. 1995 Comparison between beryllium-copper and tungsten high frequency air coplanar probes. *IEEE Trans. Microw. Theory Technol.* **43** (12), 2786–2793.

CHEN, C., TAO, Z., HERNÁNDEZ-GARCÍA, C., MATYBA, P., CARR, A., KNUT, R., KFIR, O., ZUSIN, D., GENTRY, C., GRYCHTOL, P. *et al.* 2016 Tomographic reconstruction of circularly polarized high-harmonic fields: 3D attosecond metrology. *Sci. Adv.* **2** (2), e1501333.

CHILD, C. D. 1911 Discharge from hot CaO. *Phys. Rev. Ser.* I **32** (5), 492–511.

CHIN, M., BARBER, J. R. & HU, S. J. 2006 Effect of elastic recovery on the electrical contact resistance in anisotropic conductive adhesive assemblies. *IEEE Trans. Compon. Packag. Technol.* **29** (1), 137–144.

COCKER, T. L., JELIC, V., GUPTA, M., MOLESKY, S. J., BURGESS, J. A. J., REYES, G. D. L., TITOVA, L. V., TSUI, Y. Y., FREEMAN, M. R. & HEGMANN, F. A. 2013 An ultrafast terahertz scanning tunnelling microscope. *Nat. Photon.* **7** (8), 620–625.

CORKUM, P. B. 1993 Plasma perspective on strong field multiphoton ionization. *Phys. Rev. Lett.* **71** (13), 1994–1997.

CORKUM, P. B., BRUNEL, F., SHERMAN, N. K. & SRINIVASAN-RAO, T. 1988 Thermal response of metals to ultrashort-pulse laser excitation. *Phys. Rev. Lett.* **61** (25), 2886–2889.

CORKUM, P. B., BURNETT, N. H. & IVANOV, M. Y. 1994 Subfemtosecond pulses. *Opt. Lett.* **19** (22), 1870–1872.

CORKUM, P. B. & KRAUSZ, F. 2007 Attosecond science. *Nat. Phys.* **3** (6), 381–387.

DAS, V. D. & JAGADEESH, M. S. 1981 Tunneling in Al–Al_2O_3–Al MIM structures. *Phys. Stat. Solid.* A **66** (1), 327–333.

DATTA, S. 2005 *Quantum Transport: Atom to Transistor*, 2nd edn. Cambridge University Press.

DATTA, S. & ANANTRAM, M. P. 1992 Steady-state transport in mesoscopic systems illuminated by alternating fields. *Phys. Rev.* B **45** (23), 13761–13764.

ENGLAND, R. J., NOBLE, R. J., BANE, K., DOWELL, D. H., NG, C.-K., SPENCER, J. E., TANTAWI, S., WU, Z., BYER, R. L., PERALTA, E. *et al.* 2014 Dielectric laser accelerators. *Rev. Mod. Phys.* **86** (4), 1337–1389.

ESTEBAN, R., BORISOV, A. G., NORDLANDER, P. & AIZPURUA, J. 2012 Bridging quantum and classical plasmonics with a quantum-corrected model. *Nat. Commun.* **3**, 825.

FAIRCHILD, S. B., BOECKL, J., BACK, T. C., FERGUSON, J. B., KOERNER, H., MURRAY, P. T., MARUYAMA, B., LANGE, M. A., CAHAY, M. M., BEHABTU, N. *et al.* 2015 Morphology dependent field emission of acid-spun carbon nanotube fibers. *Nanotechnology* **26** (10), 105706.

FAN, T., GRYCHTOL, P., KNUT, R., HERNÁNDEZ-GARCÍA, C., HICKSTEIN, D. D., ZUSIN, D., GENTRY, C., DOLLAR, F. J., MANCUSO, C. A., HOGLE, C. W. *et al.* 2015 Bright circularly polarized soft X-ray high harmonics for X-ray magnetic circular dichroism. *Proc. Natl Acad. Sci.* **112** (46), 14206–14211.

FENG, Y. & VERBONCOEUR, J. P. 2005 A model for effective field enhancement for Fowler–Nordheim field emission. *Phys. Plasmas* **12** (10), 103301.

FENG, Y. & VERBONCOEUR, J. P. 2006 Transition from Fowler–Nordheim field emission to space charge limited current density. *Phys. Plasmas* **13** (7), 73105.

FENG, Y. & VERBONCOEUR, J. P. 2008 Consistent solution for space-charge-limited current in the relativistic regime for monoenergetic initial velocities. *Phys. Plasmas* **15** (11), 112101.

FENG, Y., VERBONCOEUR, J. P. & LIN, M. C. 2008 Solution for space charge limited field emission current densities with injection velocity and geometric effects corrections. *Phys. Plasmas* **15** (4), 43301.

FOWLER, R. H. & NORDHEIM, L. 1928 Electron emission in intense electric fields. *Proc. R. Soc. Lond.* A **119** (781), 173–181.

GOMEZ, M. R., FRENCH, D. M., TANG, W., ZHANG, P., LAU, Y. Y. & GILGENBACH, R. M. 2009 Experimental validation of a higher dimensional theory of electrical contact resistance. *Appl. Phys. Lett.* **95** (7), 72103.

GOMEZ, M. R., ZIER, J. C., GILGENBACH, R. M., FRENCH, D. M., TANG, W. & LAU, Y. Y. 2008 Effect of soft metal gasket contacts on contact resistance, energy deposition, and plasma expansion profile in a wire array Z pinch. *Rev. Sci. Instrum.* **79** (9), 93512.

GRISWOLD, M. E. & FISCH, N. J. 2016 Maximum time-dependent space-charge limited diode currents. *Phys. Plasmas* **23** (1), 14502.

GRISWOLD, M. E., FISCH, N. J. & WURTELE, J. S. 2010 An upper bound to time-averaged space-charge limited diode currents. *Phys. Plasmas* **17** (11), 114503.

GRISWOLD, M. E., FISCH, N. J. & WURTELE, J. S. 2012 Amended conjecture on an upper bound to time-dependent space-charge limited current. *Phys. Plasmas* **19** (2), 24502.

GROSSE, K. L., BAE, M.-H., LIAN, F., POP, E. & KING, W. P. 2011 Nanoscale Joule heating, Peltier cooling and current crowding at graphene-metal contacts. *Nat. Nanotechnol.* **6** (5), 287–290.

GROTJOHN, T. A., TRAN, D. T., YARAN, M. K., DEMLOW, S. N. & SCHUELKE, T. 2014 Heavy phosphorus doping by epitaxial growth on the (111) diamond surface. *Diamond Relat. Mater.* **44**, 129–133.

HALL, P. M. 1968 Resistance calculations for thin film patterns. *Thin Solid Films* **1** (4), 277–295.

HAN, J. W. & MEYYAPPAN, M. 2014 *Introducing the Vacuum Transistor: A Device Made of Nothing*, 23 June, 2014; http://spectrum.ieee.org/semiconductors/devices/introducing-the-vacuum-transistor-a-device-made-of-nothing.

HAN, J.-W., OH, J. S. & MEYYAPPAN, M. 2012 Vacuum nanoelectronics: back to the future? – Gate insulated nanoscale vacuum channel transistor. *Appl. Phys. Lett.* **100** (21), 213505.

HARRIS, J. R., JENSEN, K. L., SHIFFLER, D. A. & PETILLO, J. J. 2015 Shielding in ungated field emitter arrays. *Appl. Phys. Lett.* **106** (20), 201603.

HOLM, R. 1967 *Electric Contacts: Theory and Application*, 4th edn. Springer.

HOMMELHOFF, P., KEALHOFER, C. & KASEVICH, M. A. 2006 Ultrafast electron pulses from a Tungsten tip triggered by low-power femtosecond laser pulses. *Phys. Rev. Lett.* **97** (24), 247402.

HOMMELHOFF, P. & KLING, M. (Eds) 2014 *Attosecond Nanophysics: From Basic Science to Applications*, 1 edn. Wiley-VCH.

ILKOV, M., TORFASON, K., MANOLESCU, A. & VALFELLS, Á. 2015 Terahertz pulsed photogenerated current in microdiodes at room temperature. *Appl. Phys. Lett.* **107** (20), 203508.

JENSEN, K. L. 2010 Space charge effects in field emission: three dimensional theory. *J. Appl. Phys.* **107** (1), 14905.

JENSEN, K. L., LAU, Y. Y., FELDMAN, D. W. & O'SHEA, P. G. 2008 Electron emission contributions to dark current and its relation to microscopic field enhancement and heating in accelerator structures. *Phys. Rev. Special Top. Accel. Beams* **11** (8), 81001.

JENSEN, K. L., SHIFFLER, D. A., RITTERSDORF, I. M., LEBOWITZ, J. L., HARRIS, J. R., LAU, Y. Y., PETILLO, J. J., TANG, W. & LUGINSLAND, J. W. 2015 Discrete space charge affected field emission: flat and hemisphere emitters. *J. Appl. Phys.* **117** (19), 194902.

KAO, K. C. 2004 *Dielectric Phenomena in Solids*, 1 edn. Academic.

KOH, W. S. & ANG, L. K. 2008 Quantum model of space–charge-limited field emission in a nanogap. *Nanotechnology* **19** (23), 235402.

LANDAUER, R. 1996 Spatial variation of currents and fields due to localized scatterers in metallic conduction (and comment). *J. Math. Phys.* **37** (10), 5259–5268.

LANGMUIR, I. 1913 The effect of space charge and residual gases on thermionic currents in high vacuum. *Phys. Rev.* **2** (6), 450–486.

LATHAM, R. V. 1995 *High Voltage Vacuum Insulation: Basic Concepts and Technological Practice*, 1 edn. Academic.

LAU, Y. Y. 2001 Simple theory for the two-dimensional Child–Langmuir law. *Phys. Rev. Lett.* **87** (27), 278301.

LAU, Y. Y., CHERNIN, D., COLOMBANT, D. G. & HO, P.-T. 1991 Quantum extension of Child–Langmuir law. *Phys. Rev. Lett.* **66** (11), 1446–1449.

LAU, Y. Y. & TANG, W. 2009 A higher dimensional theory of electrical contact resistance. *J. Appl. Phys.* **105** (12), 124902.

LI, C., THOSTENSON, E. T. & CHOU, T.-W. 2007 Dominant role of tunneling resistance in the electrical conductivity of carbon nanotube–based composites. *Appl. Phys. Lett.* **91** (22), 223114.

LIU, Y. L., ZHANG, P., CHEN, S. H. & ANG, L. K. 2015*a* Maximal charge injection of consecutive electron pulses with uniform temporal pulse separation. *Phys. Plasmas* **22** (8), 84504.

LIU, Y. L., ZHANG, P., CHEN, S. H. & ANG, L. K. 2015*b* Maximal charge injection of a uniform separated electron pulse train in a drift space. *Phys. Rev. Special Top. Accel. Beams* **18** (12), 123402.

LUGINSLAND, J. W., LAU, Y. Y. & GILGENBACH, R. M. 1996 Two-dimensional Child–Langmuir law. *Phys. Rev. Lett.* **77**, 4668.

LUGINSLAND, J. W., LAU, Y. Y., UMSTATTD, R. J. & WATROUS, J. J. 2002 Beyond the Child–Langmuir law: a review of recent results on multidimensional space-charge-limited flow. *Phys. Plasmas* **9** (5), 2371–2376.

MAKSYMOVYCH, P. 2013 Distance dependence of tunneling thermovoltage on metal surfaces. *J. Vacuum Sci. Technol.* B **31** (3), 31804.

MILLER, R., LAU, Y. Y. & BOOSKE, J. H. 2007 Electric field distribution on knife-edge field emitters. *Appl. Phys. Lett.* **91** (7), 74105.

MORTENSEN, N. A., JOHNSEN, K., JAUHO, A.-P. & FLENSBERG, K. 1999 Contact resistance of quantum tubes. *Superlatt. Microstruct.* **26** (6), 351–361.

MYÖHÄNEN, P., TUOVINEN, R., KORHONEN, T., STEFANUCCI, G. & VAN LEEUWEN, R. 2012 Image charge dynamics in time-dependent quantum transport. *Phys. Rev.* B **85** (7), 75105.

NEWNS, D. M. 1969 Fermi–Thomas response of a metal surface to an external point charge. *J. Chem. Phys.* **50** (10), 4572–4575.

NOUCHI, R. & TANIGAKI, K. 2014 Path of the current flow at the metal contacts of graphene field-effect transistors with distorted transfer characteristics. *Appl. Phys. Lett.* **105** (3), 33112.

PANT, M. & ANG, L. K. 2013 Time-dependent quantum tunneling and nonequilibrium heating model for the generalized Einstein photoelectric effect. *Phys. Rev.* B **88** (19), 195434.

PARK, M., COLA, B. A., SIEGMUND, T., XU, J., MASCHMANN, M. R., FISHER, T. S. & KIM, H. 2006 Effects of a carbon nanotube layer on electrical contact resistance between copper substrates. *Nanotechnology* **17** (9), 2294.

PEDERSEN, A., MANOLESCU, A. & VALFELLS, Á. 2010 Space-charge modulation in vacuum microdiodes at THz frequencies. *Phys. Rev. Lett.* **104** (17), 175002.

PERALTA, E. A., SOONG, K., ENGLAND, R. J., COLBY, E. R., WU, Z., MONTAZERI, B., MCGUINNESS, C., MCNEUR, J., LEEDLE, K. J., WALZ, D. *et al.* 2013 Demonstration of electron acceleration in a laser-driven dielectric microstructure. *Nature* **503** (7474), 91–94.

PORTMAN, J., ZHANG, H., TAO, Z., MAKINO, K., BERZ, M., DUXBURY, P. M. & RUAN, C.-Y. 2013 Computational and experimental characterization of high-brightness beams for femtosecond electron imaging and spectroscopy. *Appl. Phys. Lett.* **103** (25), 253115.

ROKHLENKO, A. 2015 Child–Langmuir flow with periodically varying anode voltage. *Phys. Plasmas* **22** (2), 22126.

ROKHLENKO, A. & LEBOWITZ, J. L. 2003 Space-charge-limited 2D electron flow between two flat electrodes in a strong magnetic field. *Phys. Rev. Lett.* **91** (8), 85002.

ROPERS, C., SOLLI, D. R., SCHULZ, C. P., LIENAU, C. & ELSAESSER, T. 2007 Localized multiphoton emission of femtosecond electron pulses from metal nanotips. *Phys. Rev. Lett.* **98** (4), 43907.

ROSE, A. 1955 Space-charge-limited currents in solids. *Phys. Rev.* **97** (6), 1538–1544.

RUNDQUIST, A., DURFEE, C. G., CHANG, Z., HERNE, C., BACKUS, S., MURNANE, M. M. & KAPTEYN, H. C. 1998 Phase-matched generation of coherent soft x-rays. *Science* **280** (5368), 1412–1415.

SAVAGE, K. J., HAWKEYE, M. M., ESTEBAN, R., BORISOV, A. G., AIZPURUA, J. & BAUMBERG, J. J. 2012 Revealing the quantum regime in tunnelling plasmonics. *Nature* **491** (7425), 574–577.

SCHRODER, D. K. 1998 *Semiconductor Material and Device Characterization*, 2nd edn. Wiley-Blackwell.

SHARVIN, Y. V. 1965 A possible method for studying Fermi surfaces. *Sov. Phys.-JETP* **21**, 655.

SHIFFLER, D., STATUM, T. K., HUSSEY, T. W., ZHOU, O. & MARDAHL, P. 2005 High-power microwave sources. In *Modern Microwave and Millimeter Wave Power Electronics*, p. 691. IEEE.

SIMMONS, J. G. 1963*a* Generalized formula for the electric tunnel effect between similar electrodes separated by a thin insulating film. *J. Appl. Phys.* **34** (6), 1793–1803.

SIMMONS, J. G. 1963*b* Electric tunnel effect between dissimilar electrodes separated by a thin insulating film. *J. Appl. Phys.* **34** (9), 2581–2590.

SOLOMON, P. M. 2011 Contact resistance to a one-dimensional quasi-ballistic nanotube/wire. *IEEE Electron Device Lett.* **32** (3), 246–248.

SOTTHEWES, K., HELLENTHAL, C., KUMAR, A. & ZANDVLIET, H. J. W. 2014 Transition voltage spectroscopy of scanning tunneling microscopy vacuum junctions. *RSC Advances* **4** (61), 32438–32442.

SPINDT, C. A. 1968 A thin-film field-emission cathode. *J. Appl. Phys.* **39** (7), 3504–3505.

SPINDT, C. A., BRODIE, I., HUMPHREY, L. & WESTERBERG, E. R. 1976 Physical properties of thin-film field emission cathodes with molybdenum cones. *J. Appl. Phys.* **47** (12), 5248–5263.

SRISONPHAN, S., JUNG, Y. S. & KIM, H. K. 2012 Metal-oxide-semiconductor field-effect transistor with a vacuum channel. *Nat. Nanotechnol.* **7** (8), 504–508.

STONER, B. R. & GLASS, J. T. 2012 Nanoelectronics: nothing is like a vacuum. *Nat. Nanotechnol.* **7** (8), 485–487.

TAN, S. F., WU, L., YANG, J. K. W., BAI, P., BOSMAN, M. & NIJHUIS, C. A. 2014 Quantum plasmon resonances controlled by molecular tunnel junctions. *Science* **343** (6178), 1496–1499.

TANG, W., SHIFFLER, D. & CARTWRIGHT, K. L. 2011 Analysis of electric field screening by the proximity of two knife-edge field emitters. *J. Appl. Phys.* **110** (3), 34905.

TANG, W., SHIFFLER, D., GOLBY, K., LACOUR, M. & KNOWLES, T. 2012 Experimental study of electric field screening by the proximity of two carbon fiber cathodes. *J. Vacuum Sci. Technol.* B **30** (6), 61803.

TAO, Z., CHEN, C., SZILVÁSI, T., KELLER, M., MAVRIKAKIS, M., KAPTEYN, H. & MURNANE, M. 2016 Direct time-domain observation of attosecond final-state lifetimes in photoemission from solids. *Science* **353** (6294), 62–67.

TAO, Z., ZHANG, H., DUXBURY, P. M., BERZ, M. & RUAN, C.-Y. 2012 Space charge effects in ultrafast electron diffraction and imaging. *J. Appl. Phys.* **111** (4), 44316.

TEAGUE, E. C. 1986 Room temperature gold-vacuum-gold tunneling experiments. *J. Res. Natl Bur. Stand.* **91** (4), 171–233.

TIMSIT, R. S. 1999 Electrical contact resistance: properties of stationary interfaces. *IEEE Trans. Compon. Packag. Technol.* **22** (1), 85–98.

TROUWBORST, M. L., MARTIN, C. A., SMIT, R. H. M., GUÉDON, C. M., BAART, T. A., VAN DER MOLEN, S. J. & VAN RUITENBEEK, J. M. 2011 Transition voltage spectroscopy and the nature of vacuum tunneling. *Nano Lett.* **11** (2), 614–617.

VALFELLS, Á., FELDMAN, D. W., VIRGO, M., O'SHEA, P. G. & LAU, Y. Y. 2002 Effects of pulse-length and emitter area on virtual cathode formation in electron guns. *Phys. Plasmas* **9** (5), 2377–2382.

VLAHOS, V., BOOSKE, J. H. & MORGAN, D. 2007 *Ab initio* study of the effects of thin CsI coatings on the work function of graphite cathodes. *Appl. Phys. Lett.* **91** (14), 144102.

WU, G., WEI, X., GAO, S., CHEN, Q. & PENG, L. 2016 Tunable graphene micro-emitters with fast temporal response and controllable electron emission. *Nat. Commun.* **7**, 11513.

XIA, F., PEREBEINOS, V., LIN, Y., WU, Y. & AVOURIS, P. 2011 The origins and limits of metal-graphene junction resistance. *Nat. Nanotechnol.* **6** (3), 179–184.

YAGHOOBI, P., WALUS, K. & NOJEH, A. 2009 First-principles study of quantum tunneling from nanostructures: Current in a single-walled carbon nanotube electron source. *Phys. Rev.* B **80** (11), 115422.

YALUNIN, S. V., GULDE, M. & ROPERS, C. 2011 Strong-field photoemission from surfaces: theoretical approaches. *Phys. Rev.* B **84** (19), 195426.

ZHANG, P. 2012 Effects of surface roughness on electrical contact, RF heating and field enhancement. PhD thesis, The Unviersity of Michigan, Ann Arbor.

ZHANG, P. 2015 Scaling for quantum tunneling current in nano- and subnano-scale plasmonic junctions. *Scientific Rep.* **5**, 9826.

ZHANG, P., GU, Q., LAU, Y. Y. & FAINMAN, Y. 2016 Constriction resistance and current crowding in electrically pumped semiconductor nanolasers with the presence of undercut and sidewall tilt. *IEEE J. Quantum Electron.* **52** (3), 2000207.

ZHANG, P. & HUNG, D. M. H. 2014 An analytical model for ballistic diode based on asymmetric geometry. *J. Appl. Phys.* **115** (20), 204908.

ZHANG, P., HUNG, D. M. H. & LAU, Y. Y. 2013 Current flow in a 3-terminal thin film contact with dissimilar materials and general geometric aspect ratios. *J. Phys.* D*: Appl. Phys.* **46** (6), 65502.

ZHANG, P. & LAU, Y. Y. 2010 Scaling laws for electrical contact resistance with dissimilar materials. *J. Appl. Phys.* **108** (4), 44914.

ZHANG, P. & LAU, Y. Y. 2013 Constriction resistance and current crowding in vertical thin film contact. *IEEE J. Electron Devices Soc.* **1** (3), 83–90.

ZHANG, P. & LAU, Y. Y. 2014 An exact field solution of contact resistance and comparison with the transmission line model. *Appl. Phys. Lett.* **104** (20), 204102.

ZHANG, P. & LAU, Y. Y. 2016 Ultrafast strong-field photoelectron emission from biased metal surfaces: exact solution to time-dependent Schrödinger equation. *Scientific Rep.* **6**, 19894.

ZHANG, P., LAU, Y. Y. & GILGENBACH, R. M. 2011 Thin film contact resistance with dissimilar materials. *J. Appl. Phys.* **109** (12), 124910.

ZHANG, P., LAU, Y. Y. & TIMSIT, R. S. 2012 On the spreading resistance of thin-film contacts. *IEEE Trans. Electron Devices* **59** (7), 1936–1940.

ZHANG, P., LAU, Y. Y. & GILGENBACH, R. M. 2015*a* Analysis of current crowding in thin film contacts from exact field solution. *J. Phys.* D*: Appl. Phys.* **48** (47), 475501.

ZHANG, P., LUGINSLAND, J. W., LAU, Y. Y., BOOSKE, J. H., GILGENBACH, R. M., JENSEN, K. L., PECKERAR, M., SHIFFLER, D., FAIRCHILD, S., VERBONCOEUR, J. P. *et al.* 2015*b* Ultrafast and nanoscale interfacial charge transport and its interaction with electromagnetic waves. In *DoE Whitepaper on the Frontiers of Plasma Science*. https://www.orau.gov/plasmawkshps2015/whitepapers.htm.

ZHANG, X.-G., LU, Z.-Y. & PANTELIDES, S. T. 2006 First-principles theory of tunneling currents in metal-oxide-semiconductor structures. *Appl. Phys. Lett.* **89** (3), 32112.

ZIEGLER, M., HARNACK, O. & KOHLSTEDT, H. 2014 Resistive switching in lateral junctions with nanometer separated electrodes. *Solid-State Electron.* **92**, 24–27.

ZIER, J., GOMEZ, M. R., FRENCH, D. M., GILGENBACH, R. M., LAU, Y. Y., TANG, W. W., CUNEO, M. E., MEHLHORN, T. A., JOHNSTON, M. D. & MAZARAKIS, M. G. 2008 Wire-tension effects on plasma dynamics in a two-wire -pinch. *IEEE Trans. Plasma Sci.* **36** (4), 1284–1285.