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Electron Emission and Gas Breakdown: Unification of Theory from Schrodinger's Equation to Paschen's Law

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The continued miniaturization of electronic devices for applications including micro- and nano-electromechanical systems (MEMS and NEMS, respectively) and microplasmas requires a thorough understanding of electron emission behavior at these length scales for various pressures. Paschen's law (PL) governs classical gas breakdown, but fails for microscale gaps, where field emission (FE) drives breakdown. Reducing the gap size below microscale further necessitates understanding the transitions from FE-driven breakdown to space-charge limited emission (SCLE) with Mott-Gurney (MG) at pressure, Child-Langmuir (CL) at vacuum, and quantum behavior at nanoscale. While piecewise connections of these breakdown and emission mechanisms have been studied, a complete analysis connecting all mechanisms remains incomplete.
This study aims to fill this gap by nondimensionalizing the governing equations with a consistent set of scaling parameters to obtain a single, material-dependent parameter retained in PL. Thus, this study provides a universal (material-independent) set of equations characterizing electron emission behavior from quantum scales up to, but not including, the traditional PL. The universality of the dimensionless equations highlights the underlying physics driving each mechanism and demonstrates the respective regions of importance. These dimensionless equations can predict the specific emission characteristics for a given set of experimental parameters and provide insight into device design.

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