Geometrical Optimization of Vacuum Nanoelectronics Using a Stochastic Non-Gradient Method

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Vacuum channel nano-electronic devices[1] have enjoyed a recent resurgence in the research community. Modern nanofabrication methods allow for fabricating field-emission electrodes with gaps on the 10-nm scale[2]. Nano vacuum electronics are exciting for several reasons: (1) ballistic electron transport gives rise to ultrafast, attosecond-to-femtosecond-scale response times; (2) they have been shown to be robust to radiation and temperature changes making them useful for operation in harsh conditions (e.g. space); and (3) the nanometer-scale gap provides an effective vacuum even in ambient conditions due to the vanishingly low probability of an air molecule being present.

Efforts at intuitive designs of planar nano vacuum channel devices have resulted in devices which exhibit desirable properties but suffer from low emission and robustness issues.
To address these concerns, we implemented a flexible shape optimization scheme for inverse design of a field emitter. For our optimization we used MATLAB's simulated annealing optimizer around FEniCS[3]. We ran the optimizer with different cost functions, some of which encourage total emission and some which encourage emission in the direction of the collector.
In some cases, the algorithm converges to an emitter with a sharp concave tip which increases the field enhancement. In other cases, the algorithm favors a bulb shape tip, which increases the surface area of the emitter where the electric field is strong. The bulb shaped tip might be advantageous because it's easier to fabricate and is potentially more robust than a sharp tip.

Algorithmic design of an emitter tip is the first step towards creating an optimization scheme for a fully operating device which includes the effects of gate effects on emission and particle trajectory. We are working on extending our work in that direction, and we believe that it will unlock a whole class of unintuitive nano-vacuum device topologies

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[1] J. W. Han, D. Moon, and M. Meyyappan "Nanoscale Vacuum Channel Transistor" Nano Lett. 17, 4, 2146–2151 (2017)

[2] R. Bhattacharya, M. Turchetti, P. D. Keathley, K. K. Berggren, and J. Browning "Long term field emission current stability characterization of planar field emitter devices, Journal of Vacuum Science & Technology B 39, 053201 (2021)

[3] H. P. Langtangen and A. Logg "Solving PDEs in Python" Springer (2017)

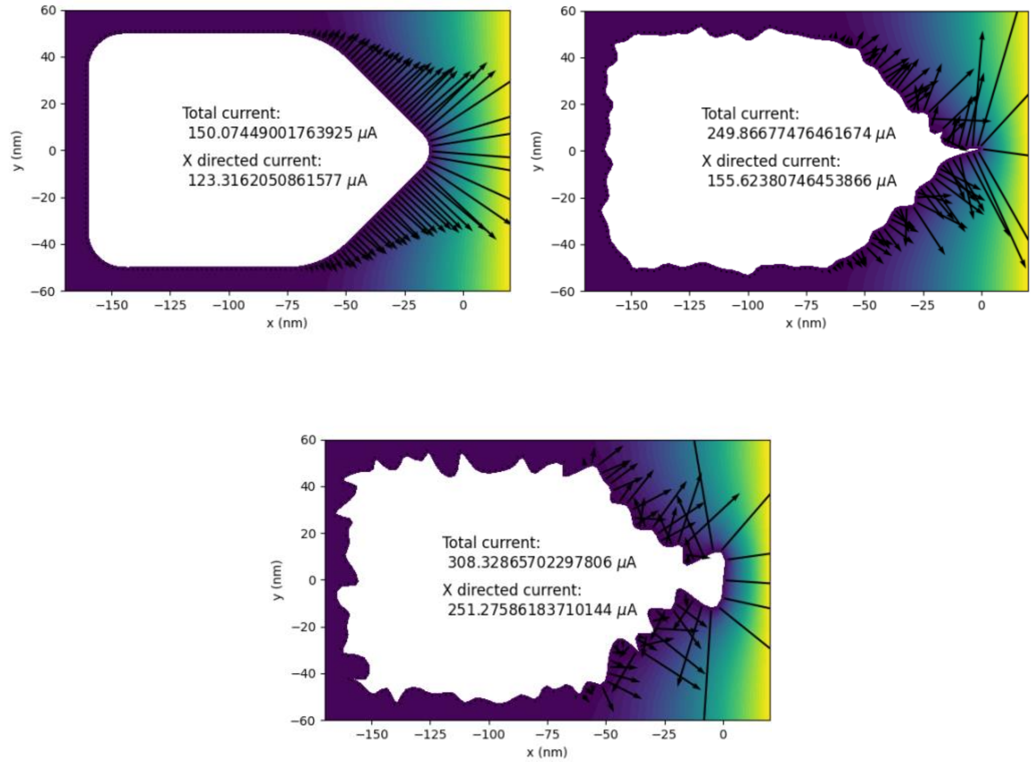

Figure 1: Initial and optimized devices: Potential and emission current for devices where the emitter is at ground potential and the collector is at 15V. *Top left:* Initial device geometry. *Top right:* Optimized device after 1000 iterations with the cost function = - x directed current + perimeter. *Bottom:* Optimized device after 10000 iterations with the cost function = perimeter/total current. In both cases, the annealing algorithm moved the parameter points along the normal to the perimeter, but in the former the step size decreased with each iteration, while in the latter it remained constant throughout.