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Design of compact klystron amplifier using Field-emitter-arrays (FEA)-based cathode

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Abstract – There has been an interest to develop an efficient, compact microwave device using field-emitter-arrays(FEA)-based cathode. To evaluate the optimum device-efficiency in a compact size, the propagation properties of the premodulated electron beam for the FEA-based cathode is studied in detail by the computer simulation using a PIC code, MAGIC. For the premodulated electron beam whose phase of the energy leads the phase of the current by $\pi/2$, the amplitude of the downstream current modulation can be kept as high as the initial modulation level. Using the beam parameters with the beam voltage of 6 kV and the current of 0.2 A, 30% of efficiency is predicted when the quality factor of 800 is chosen. The device length is reduced about twice compared with that of the conventional device. The design of practical planar cathode is carried out to meet the minimum diameter of the electron beam as 0.5 mm.

I. Introduction

Premodulated electron beam has been investigated for the applications to high-power amplifiers such as the traveling wave tube (TWT) and klystron [1,2]. Premodulated beams may allow extremely compact amplifier devices by eliminating the amplification regions. For producing premodulated beams, field emitter arrays (FEAs) have been recognized as a promising candidate for use in power amplifiers due to their high current density capabilities [3, 4]. With a large initial current modulation, it may be possible to reduce considerably the size of the amplification region. Recently, a nonlinear theory of a prebunched electron beam propagating through a drift tube has been reported [5]. The theory and experiment of typical klystron modulation has been carried out [6]. In this work, to design the compact klystron amplifier using FEA-based cathode, we investigate the propagation properties and cavity excitation by the prebunched electron beam using a computer simulation (PIC code, MAGIC). In this simulation, the influence of the initial energy modulation of the prebunched electron beam during propagation is investigated. The observation is made by the simulation on the current and energy modulations of an electron beam propagating downstream, when the energy and current of electron beam are simultaneously premodulated at the injection point. When the prebunched electron beam enters the drift tube, the initial beam current is modulated according to a prescribed current profile $f(\omega t)$, where ω is the modulation frequency of the beam. In addition to initial current modulation, we may also modulate the beam energy at the beginning with some phase difference between current and energy modulation. The initial energy modulation plays an important role in current modulation as the beam propagates downstream.

One way of introducing the initial energy modulation is installation of an idle cavity at the beginning of the tube. Another way is placing an FEA-based cathode in the cavity. By tuning the cavity the phase difference between the energy modulation and current modulation can be introduced.

In addition to the study on beam propagation, a cavity excitation by the premodulated electron beam is investigated using a computer simulation. The saturated efficiency is estimated when the quality factor of the cavity is varied.

A conventional electron gun has a concave shaped cathode. It is not easy to fabricate the concaved cathode using FEAs. So an electron gun of planar cathode is designed for an electron beam whose voltage is 6 kV, beam current is 0.2 A, and the minimum diameter is 0.5 mm. The emission current density of the cathode using FEA-tips is assumed to be 7.0 A/cm^2.

II. Results of Computer Simulation

2.1. Propagation Characteristics of Premodulated Electron Beam

The behavior of the premodulated solid electron beam which propagates through the drift tube under the guiding magnetic field is simulated using a particle-in-cell code, MAGIC. As described in the previous section, the beam premodulation is done at the cathode. In this simulation, modulation is set up at the beginning of the 65 mm-long drift tube. The beam current of 0.1 A and the beam voltage of 4 kV with the beam radius of 1 mm are used here. The filling factor of the beam in the drift tube is 0.25. To ignore scalloping effect of the electron beam, the magnitude of external magnetic field is chosen to be six times the Brillouin magnetic field for the confined flow. The current modulation is modeled as $f(\omega t)=1-0.8 \cos \omega t$ where, ω is the modulation frequency. The beam current is highly modulated at the beginning and an arbitrary large value of 0.8 for the modulation strength is chosen in this simulation. The frequency (ω) of the initial current modulation is assumed to be 10 GHz.

The total A.C. current of the electron beam propagating downstream is measured at every 2 mm distance during 10 nsec and also Fourier-decomposed to investigate the mode evolution. The mode strengths of fundamental mode and higher harmonics up to four are compared. With several strengths of the initial energy modulation (ε), and the phase difference (α) between the initial current and energy modulation, the propagation properties of fundamental mode component of A.C. current amplitude are observed.

Fig. 1 shows the evolution of the fundamental mode components of the current modulation in an electron beam propagating downstream. The mode evolution labeled by pre-bunched current is obtained from the computer simulation of an electron beam with premodulated current at the cathode. On the other hand, the mode evolution labeled by velocity modulation is obtained from the simulation of a beam conventionally velocity-modulated at the input cavity. The peak A.C. current of the premodulated electron beam has the maximum value at the beginning and decreases as the beam propagates downstream of the drift tube due to its space charge. As well known, the A.C. current of the conventional velocity modulation is determined by the input power level and modulation frequency which is determined by the resonant frequency of the input cavity.

Elimination of the input cavity should not only reduce the size of the device but also potentially increase the efficiency of the device. The output cavity is placed as close as possible. However, due to the physical space of the device, maximum strength of the A.C. current can not be acquired. Typical current of the premodulated beam is shown in Fig. 2, where a snap-shot of the current modulation of the downstream beam is taken. Fig. 2 exhibits a D.C. current at z=2.3 cm. This is consistent

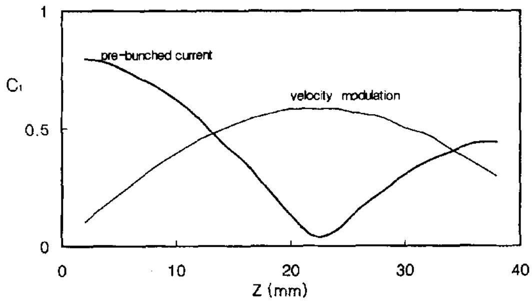

Fig. 1. Comparison of bunchings for the premodulated current and the conventional energy modulation.

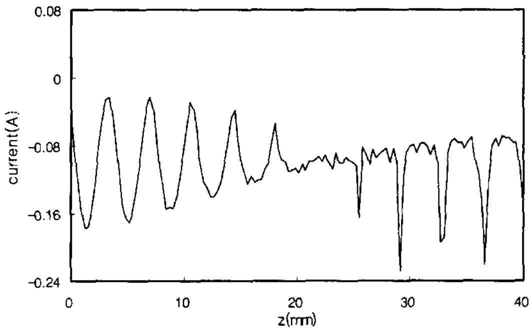

Fig. 2. Typical current of premodulated beam propagating downstream obtained from computer simulation.

with Fig. 1, where current modulation of the beam vanishes at z=2.3 cm for the pre-bunched current.

In this work, one way of recovering this debunching effect is studied by introducing the energy and current modulation at the cathode. The energy modulation can be realized in practice by placing an idle cavity at the cathode. Therefore, the energy modulation is modeled as $g(\omega t)=-\varepsilon\cos(\omega t + \alpha)$ where, ε is the strength of the initial energy modulation which is normalized by the electron beam voltage, α is the initial phase difference between the energy and current modulations which can be achieved by mismatch in resonant frequency of an idle cavity with modulation frequency.

Fig. 3 shows a plot of the amplitude of fundamental mode component (ω) versus the propagation distance (z) for several different values of the energy modulation strength ε. Here, the phase difference, α, is chosen to be zero. The curve labeled by ε=0.0 in Fig. 3 is identical to the curve labeled by pre-

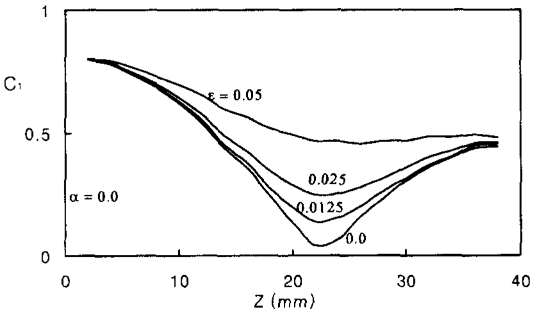

Fig. 3. Fundamental mode strength c_1 versus propagation diatance z obtained from computer simulation for α=0.0 and several different values of the initial energy modulation ε.

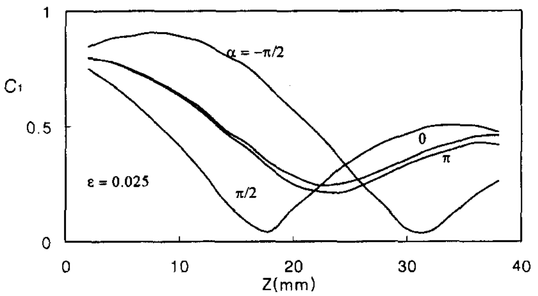

Fig. 4. Plots of the fundamental mode strength c_1 versus propagation diatance z obtained computer simulation for ε=0.025 and several different values of the initial energy modulation α.

bunched current in Fig. 1.

It is observed that the distance at which the amplitude of A.C. current is minimized is not sensitive to the strength of the initial energy modulation ε. But with a larger value of the energy modulation strength ε, the modulated current can propagate a considerable distance without serious deterioration of the modulation amplitude.

Fig. 4 shows plot of the A.C. current amplitude versus the propagation distance (z) for different values of the initial phase difference α. Here, ε is chosen as 0.025. The very small difference between the cases for α=0 and $\alpha=\pi$ may be caused by the numerical error on the computer simulation due to a limited simulation time for Fourier transformation. It is observed from Fig. 4 that the current modulation strength for $\alpha=\pi/2$ comes down to a minimum value at z=17 mm which is significantly less than those of α=0 and $\alpha=\pi$. For $\alpha=-\pi/2$, the modulation amplitude comes down to the minimum value at z=32 mm. The modulation amplitude for $\alpha=-\pi/2$ increases near the injection point and the beam can propagate a considerable distance without deterioration. It means that an appropriate initial energy-modulation can maintain the amplitude of the downstream current modulation as high as the initial level. The similar behavior can also be observed in a detuned penultimate cavity of a conventional multicavity klystron [7, 8].

Fig. 5(a) and (b) show plot of the Fourier transformation of modulated current measured at the beginning and at downstream in the drift tube. The fundamental mode is prevailing and the others are very weak at the beginning, but as the beam propagates, amplitude of the fundamental mode is getting smaller while the others are growing. Fourier decomposition is performed to observe the evolution of fundamental mode component during the beam propagates.

Fig. 6(a) and (b) show that the strength of the fundamental and high harmonic components versus propagating distance. The first four lowest modes are chosen because the other higher modes contribution is negligibly small. Fig. 6(a) is for $\alpha=-\pi/2$ and Fig. 6(b) for $\alpha=\pi/2$. The energy modulation strength is 0.025 for both cases. The fundamental mode prevails until the beam debunches completely.

It is seen that the initial energy modulation plays

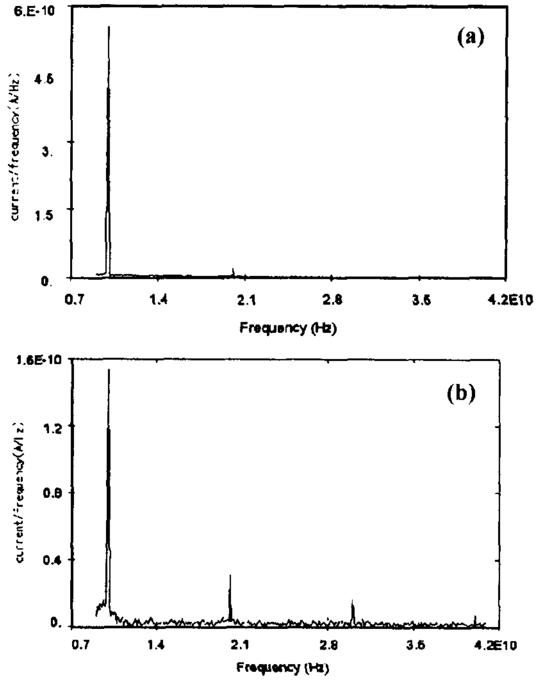

Fig. 5. FFT of current measured at propagation distance obtained from computer simulation. (a) z=2 mm, (b) z=24 mm.

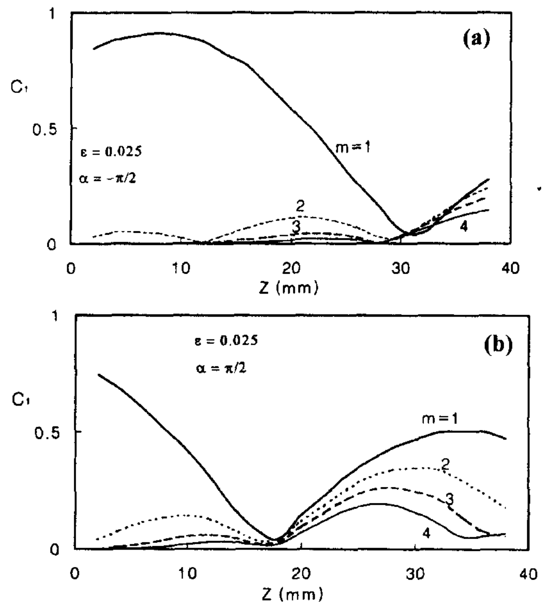

Fig. 6. Mode strength of m=1, 2, 3, 4 obtained from computer simulation for (a) ε=0.025 and α=-π/2, (b) ε=0.025 and α=π/2.

an important role in current modulation as the modulated electron beam propagates downstream. With appropriate initial energy modulation, amplitude of the downstream current modulation can be maintained as high as the initial modulation level.

2.2. Cavity Excitation by Premodulated Electron Beam

Computer simulation is carried out for the cavity excitation by the premodulated electron beam using particle-in-cell code, MAGIC. In this simulation, the premodulated beam whose phase of energy leads phase of current by π/2 is used. It means that the phase difference α between the initial current and energy modulation is -π/2. The beam current of 0.2 A and the beam voltage of 6 kV with the beam radius of 0.5 mm are used here. The filling factor of the beam in the drift tube is 0.25. To ignore the scalloping effect in the electron beam, the external magnetic field is chosen as six times the Brillouin magnetic field for the confined flow. The current modulation is modeled as $f(\omega t)=1-h\cos\omega t$ where, ω is the modulation frequency. The frequency of the initial current modulation is given by 5.045 GHz. This frequency is used for microwave landing system such as in airport. The output cavity is positioned at 3 mm apart from the cathode where the amplitude of A.C. current is peak.

There are two important parameters in cavity excitation. Such as the resonant frequency of the cavity and the quality factor of the cavity. Fig. 7 shows a transient behavior of the induced voltage at the output cavity for several values of frequency detunings η. Here, the quality factor Q is chosen as 1000. It is shown that the amplitude of induced voltage indi-

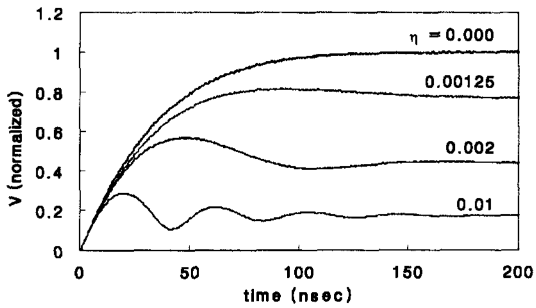

Fig. 7. Transit behavior of induced voltage at output cavity gap for several values of frequency detunings when Q=1000. The induced voltage is normalized.

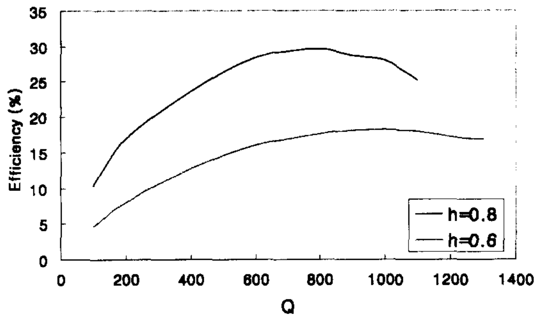

Fig. 8. Efficiency versus Q's.

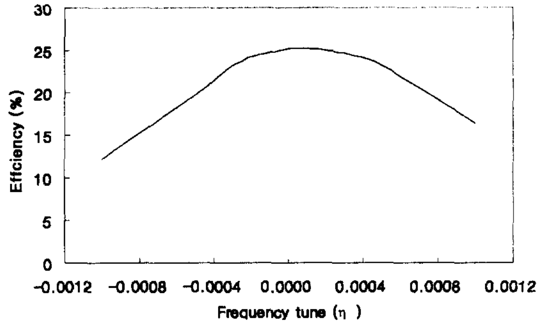

Fig. 9. Effiency versus frequency detune parameter η.

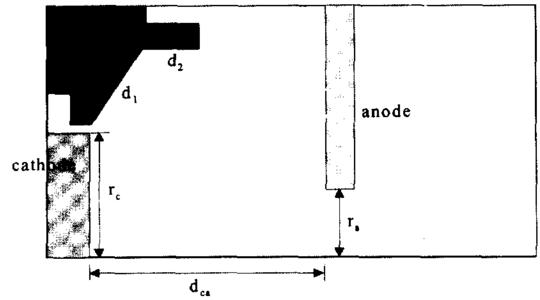

Fig. 10. Schematic diagram of electron gun using planar cathode.

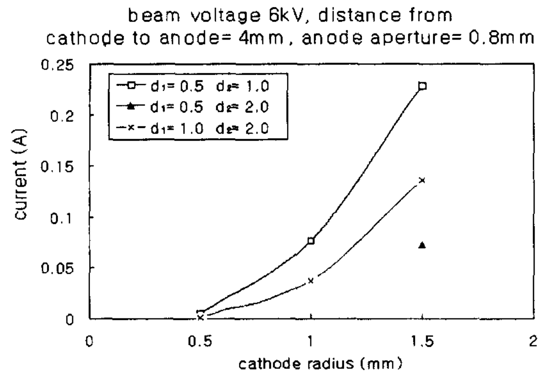

Fig. 11. Current v.s. cathode radius.

cates a damping oscillation. The induced voltage approaches the steady-state value with the time.

To measure the energy extracted from the kinetic energy of the electron beam to RF energy, we measure the energy of the electron beam at the injection point and at the end point of the simulation respectively. The electron beam loses its kinetic energy during traveling through the cavity.

Efficiency is simulated when the quality factor of the cavity is varied. Fig. 8 shows the saturation of efficiency at an optimum value of the quality factor (~800). If the quality factor (Q) increases the frequency selectivity becomes larger, that is, the bandwidth is very narrow. Fig. 9 shows the result of computer simulation for efficiency versus frequency detune parameter η, which is defined as $\eta = (\omega_0 - \omega)/\omega_0$. The predicted efficiency is simulated while the resonant frequency of the cavity is detuned.

2.3. Design of Planar Cathode-electron Gun

The schematic diagram of the electron gun for this simulation is shown in Fig. 10. Varying the radius of the planar cathode from 0.5 mm to 2.0 mm with 0.5 mm step, the current, axial velocity spread and minimum radius of electron beam are obtained from simulation. For each case, the position of anode and the shape of focusing electrode are changed. So it is found that the position of anode and the shape of focusing electrode for an electron beam of 6 kV, 0.2 A.

The simualtion results are summarized as follows. Fig. 11 shows the current versus the change of the cathode radius. As shown in Fig. 11, it is difficult to get an adequate current when the radius of cathode is less than 1.0 mm. However the closer the anode is to cathode, the larger current is emitted with the same shape of cathode and focus electrode. The radius of cathode should be larger than 1.5 mm to emit the desired beam current.

Due to the short distance between the anode and the cathode, the beam interception into the anode and the shaping of the focus electrode are carefully considered in the design.

Fig. 12 shows the current versus the distance between a anode and a cathode. The distance of the anode to the cathode is chosen 4 mm to obtain the larger current. The current of the electron beam

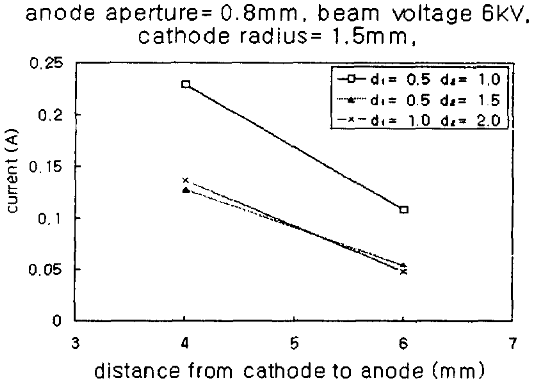

Fig. 12. Current v.s. cathode anode distance.

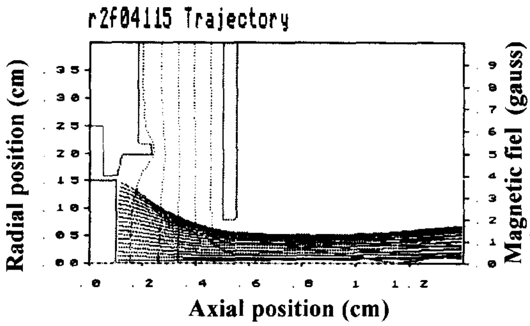

Fig. 13. Simulation result of electron gun using planar cathode.

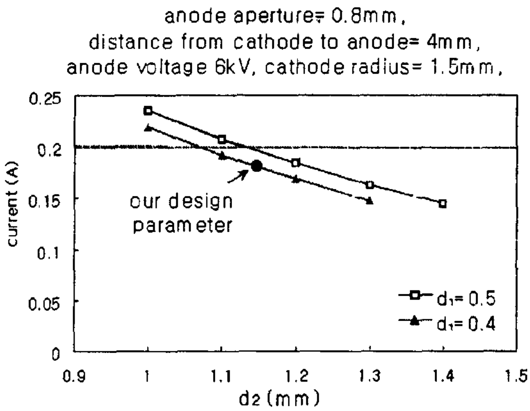

Fig. 14. Current v.s. shape of focus electrode.

decreases and the minimum radius of electron beam increases when the radius of the anode increases. Therefor, the smaller radius of the anode is desirable. Fig. 13 shows the simulation output of the electron gun using a planar cathode by e-gun code.

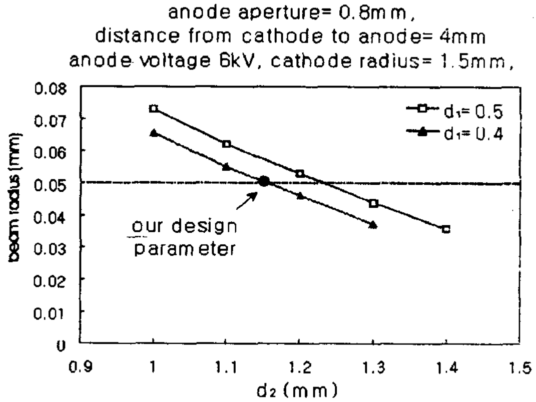

Fig. 15. Beam radius v.s. shape of focus electrode.

The plots for the current versus the size of d_1 and d_2 are shown in Fig. 14 and 15, respectively. The radius of the cathode (r_c) is 1.5 mm, the distance between the anode and the cathode (d_{ca}) is 4.0 mm, the radius of the anode (r_a) is 0.8 mm and the lengths of the focusing electrode (d_1 and d_2) are 0.4 mm and 1.15 mm, respectively. In this case, the current of the electron beam is 0.18 A, the minimum radius of the electron beam is 0.51 mm (Fig. 15), the axial position where the radius of electron beam is minimized is 0.838 cm, and the axial velocity spread is 0.104%.

III. Conclusion

To design a compact klystron amplifier using FEA-based cathode, a computer simulation is carried out using a particle-in-cell code, MAGIC. The initial energy modulation plays an important role in current modulation as the beam propagates downstream. With an appropriate initial energy-modulation, the amplitude of the current modulation can be kept as high as the initial current-modulation level. This means that the modulated current can propagate a considerable distance without deterioration of modulation amplitude. The appreciable growth of high harmonic components is also observed as the electron beam debunches.

The cavity excitation by the premodulated electron beam is also investigated by the computer simulation. This simulation is carried out to investigate the influence of quality factor Q on energy transfer from kinetic energy of the electron beam to the electromagnetic energy induced in the output cavity. It is observed that there is an optimum Q value for the energy dependign on the initial current modulation strength. Presence of the optimum Q indicates that there is a nonlinear effect in interaction between the modulated electron beam and the electromagnetic field at gap of output cavity when the electric field is strong enough. This nonlinear effect causes a deterioration of the electron bunching.

To produce the 6 kV, 0.2 A electron beam with the minimum diameter of 0.5 mm, a planar cathode-electron gun using FEA-tips is designed by the computer simulation. The predicted axial velocity spread is estimated as 0.104%.

References

[1] M. A. Kodis, H. P. Freund, N. R. Vanderplaats, and E. G. Zaidman, *Technical Digest of the International Electron Devices Meeting* 1991, Washington, D. C. (Institute of Electrical and Electronic Engineers, New York, 1991), Vol. I, p. 589.

[2] K. Nguyen, G. Warren, L. Ludeking, and B. Goplen, *IEEE Trans. Electron Devices*, **38**, 2212 (1991).

[3] R. K. Parker, K. L. Jensen, R. H. Abrams, *Technical Digest of 10th International Vacuum Microelectronics Conference*. p. 92, Kyongju, Korea (1997).

[4] E. G. Zaidman and M. A. Kodis, *IEEE Trans. Electron Dev.* **38**, 2221 (1991).

[5] H. S. Uhm, G. S. Park, and C. M. Armstrong, *Phys. Fluids* B **5**, 1349 (1993).

[6] M. Friedman, J. Krall, Y. Y. Lau, and V. Serlin, *IEEE Trans. Plasma Science* **18**, 553 (1990).

[7] T. G. Mihran, et al., *IEEE Trans. Electron Dev.* **ED-18**, 124 (1971).

[8] T. M. Tran, et al., *Phys. Fluids*, **29**, 1274 (1986).