An Integrated Floating-Electrode Electric Microgenerator

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Abstract—Microfabricated electric generators, scavenging ambient mechanical energy, are potential power sources for autonomous systems. Described presently are the design, modeling, and implementation of a *single-wafer* floating-electrode electric microgenerator, integrating a micromechanical resonator and a number of electronic devices. Forming a plate of a variable capacitor, the resonator is responsible for converting mechanical vibration to electricity. A sense transistor and a diode bridge are integrated, respectively, for monitoring the “charging” of the floating electrode and for rectification. A lumped electromechanical model of the generator is developed and expressed in terms of a set of nonlinear coupled state equations that are numerically solved. For small-amplitude excitation, a circuit based on a set of linearized equations is developed. The generator is realized using a compatible combination of standard complementary metal–oxide–semiconductor (CMOS) “floating gate” process and a post-CMOS photoresist molded electroplating process. Adequate agreement between model predictions and measurement results was obtained. [1691]

Index Terms—Electroplating, electrostatic microelectromechanical systems (MEMS) device, energy scavenging, post-complementary metal–oxide–semiconductor (CMOS), power generator.

I. INTRODUCTION

MICROFABRICATED systems converting vibration to electricity could be employed to scavenge ambient mechanical energy that otherwise would be wasted. Such electric microgenerators are particularly useful for powering miniaturized systems operating in poorly accessible or hostile environments. The three physical principles more popularly employed for realizing electric microgenerators are electromagnetic [1], electrostatic [2], and piezoelectric [3]. Electrostatic is a good solution for the construction of microgenerators because of its relative ease of integration with microelectronics. The technology of microfabrication enables the creation of

electrostatic generators employing miniaturized, capacitive electromechanical transducers.

An electrostatic electromechanical transducer consists of a variable capacitor with electrodes capable of executing a relative motion. One of the electrodes is typically implemented using a permanently charged electret. Some examples of recently implemented microgenerators are listed in Table I. All of these implementations call for the assembly of two separate substrates, one containing a mechanical resonator and another containing the electret. Such assembly requires a nontrivial alignment of the substrates that hinders scaling and optimal operation of the generators.

In this implementation, the modeling, fabrication, and characterization of a *single-wafer* integrated floating-electrode electrostatic electric microgenerator are described. The electret is replaced by an insulated floating-electrode made of heavily doped polycrystalline silicon (poly-Si) and fabricated using a standard CMOS “floating gate” process [7]. Charged by electron tunneling, the floating electrode works like one in a conventional nonvolatile memory device. A mechanical resonator, which forms a counter plate to the floating electrode, is realized using a photoresist molded low-temperature electroplating process [8] that is compatible with the construction of the floating electrode. A sense transistor and a diode bridge are integrated, respectively, for monitoring the “charging” of the floating electrode and for rectification.

A lumped-element electromechanical model of the microgenerator is developed and described in terms of a set of nonlinear, coupled state equations that are numerically solved using SIMULINK [9]. For small-amplitude excitation, a circuit based on a set of linearized equations is developed. The fabricated generators were tested using a shaker as a source of vibration. Reasonable agreement between model predictions and measurement results was obtained.

II. DESIGN AND MODELING

Shown in Fig. 1 is the schematic design of the microgenerator. An electrically floating electrode made of heavily doped poly-Si is insulated on all sides by a low-stress silicon nitride. This electrode, together with a movable metallic electrode as the counter plate, forms a variable capacitor C_{cf} . It is charged by electron tunneling through a thin oxide thermally grown inside a window opened on an insulating silicon nitride. The metallic electrode functions as a laterally oscillating mechanical resonator with a loop-spring design [8]. Since significant relative displacement between the electrodes of C_{cf} is possible, several cycles of variation of C_{cf} between its maximum C_{cf_max} (fully overlapped)

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TABLE I
RECENTLY IMPLEMENTED ELECTRET POWER MICROGENERATORS

Source	Relative motion (Capacitor gap space)	Electret (Charge density)	Remark
Boland <i>et al</i> [4]	Rotational (~80μm)	Dupont Teflon AF 1601-S (-0.28mC/m ²)	Frequency: 70Hz Power: 25μW Diameter = 8mm
Sterken <i>et al</i> [5]	Lateral (2.2μm)	SOI MPW service (Not reported)	Frequency: 980Hz Power: 1μW Size: 2.4x1.1mm ²
Arakawa <i>et al</i> [6]	Lateral (300μm)	Asahi Glass CYTOP (-0.68mC/m ²)	Frequency: 10Hz Power: 6μW Size: 20x20mm ²

Fig. 1. Schematic diagrams of (a) a 2×2 array generator and (b) a magnified view of the resonator over the fixed floating electrode of the generator.

and minimum C_{cf_min} (fringe) values are possible within one vibration period.

Larger output power can be obtained by linking an array of identical resonators with rigid coupling beams [10]. This alleviates potential rigidity problems associated with a single large resonator. Furthermore, array size (hence power) can be readily scaled, while largely preserving the designed natural vibration frequency of the component resonators.

Shown in Fig. 2 is a lumped-element schematic representation of the microgenerator. It is assumed that the floating electrode is fixed to the vibration frame. The variable capacitance C_{cf} is approximated by that of a one-dimensional capacitor, i.e., $C_{cf} \approx (\epsilon_o a/h)(b - |x - y|)$, where x is the displacement of the resonator with respect to an arbitrary but fixed origin and y is the displacement of the vibration frame (hence also the floating electrode) with respect to the same origin. ϵ_o is the dielectric constant of air; h is the gap spacing between the electrodes; a is the total effective width of the capacitor electrodes normal to the direction of motion; and b is the length of the electrodes

Fig. 2. Lumped-element electromechanical model of the microgenerator.

along the direction of motion. The resonator is modeled as a spring-mass system with a dashpot damper [11]. Mechanical vibration leads to changes in the relative displacement $x - y$. Consequently, C_{cf} changes between $C_{cf_max} \approx \epsilon_o(ab/h)$ when $|x - y| = 0$ and $C_{cf_min} \approx 0$ when $|x - y| = b$. Vibration leads to the generation of an alternating current flowing through an external load resistor R_L and a parasitic capacitor C_L .

Mechanical and electrical energy conversion is coupled through the electrostatic field across the plates of C_{cf} . The force F_{e-x} acting on the field and the voltage V_{em} generated across C_{cf} can be derived from appropriate partial differential coefficients of the total electrostatic energy $W_e \equiv (1/2)(Q^2/C_{cf})$ stored in the coupling field [12]

$$F_{e-x} \equiv \frac{\partial W_e}{\partial x} \bigg|_{Q,y} \approx \frac{1}{2} \frac{Q^2}{C_{cf}^2} \frac{\partial C_{cf}}{\partial x} \bigg|_y$$

$$= \text{sgn}(x - y) \frac{Q^2}{2C_{cf}^2} \frac{\epsilon_o a}{h} \quad (1)$$

$$V_{em} \equiv \frac{\partial W_e}{\partial Q} \bigg|_{x,y} \approx \frac{Qh}{\epsilon_o a(b - |x - y|)} = \frac{Q}{C_{cf}} \quad (2)$$

where it is assumed that there are no other energy loss mechanisms. Q is the instantaneous charge on C_{cf} . The function $\text{sgn}(x - y) = 1$ if $x \geq y$ and -1 if $x < y$.

Fig. 3. Dynamic model of the microgenerator built in SIMULINK.

The mechanical resonator is governed by Newton's second law

$$M \frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + k(x - y) + F_{e-x} = 0 \quad (3)$$

where M is the lumped mass of the resonator, β is the damping coefficient, k is the equivalent lumped spring constant, and $-F_{e-x}$ is the force acting on M by the coupling field.

The electrical part of the system is governed by Kirchoff's voltage law

$$\left(\frac{C_{cf}C_L + C_{fg}C_L + C_{fg}C_{cf}}{C_{fg}C_{cf}} \right) \frac{dQ}{dt} = \frac{Q_f}{C_{fg}} \frac{1}{R_L} - \left[\frac{C_L}{C_{cf}^2} \frac{\epsilon_0 a}{h} \text{sgn}(x - y) \frac{d}{dt}(x - y) + \frac{C_{cf} + C_{fg}}{C_{fg}C_{cf}R_L} \right] Q \quad (4)$$

where C_{fg} is the fixed floating-electrode to ground (the substrate) capacitance, C_L is a parasitic capacitance, and Q_f is the net charge stored on the floating electrode. Setting $C_L = 0$, one recovers the differential equation [13] governing the case without the parasitic capacitive loading.

It can be seen in (1) that the term F_{e-x} in (3) displays a quadratic dependence on Q and the term $1/C_{cf} \approx (h/\epsilon_0 a)(1/b - |x - y|)$ in (4) is nonlinear in $x - y$. Consequently, (3) and (4) are coupled and nonlinear.

A. Large-Amplitude Solution

Due to the difficulty in obtaining closed-form solutions to (3) and (4), a numerical approach based on a set of state differential equations is presently adopted [14]. In this approach, a given state of the system is described by a set of state variables, the time derivatives of which are determined by the present values of the state and input variables.

Fig. 4. Linear circuit network of the microgenerator.

Denoting Q , x , and dx/dt by the respective state variables X_1 , X_2 , and X_3 , (3) and (4) can be converted to the following set of three state equations:

$$\left(\frac{C_{cf}C_L + C_{fg}C_L + C_{fg}C_{cf}}{C_{fg}C_{cf}} \right) \frac{dX_1}{dt} = \frac{Q_f}{C_{fg}} \frac{1}{R_L} - \left[\frac{C_L}{C_{cf}^2} \frac{\varepsilon_o a}{h} \text{sgn}(x-y) \frac{d}{dt}(x-y) + \frac{C_{cf} + C_{fg}}{C_{fg}C_{cf}R_L} \right] X_1 \quad (5)$$

and

$$\frac{dX_2}{dt} = X_3 \quad (6)$$

$$\frac{dX_3}{dt} \approx -\frac{1}{M} \left[\beta X_3 + k(X_2 - y) + \text{sgn}(X_2 - y) \frac{X_1^2}{2C_{cf}^2} \frac{a\varepsilon_o}{h} \right] \quad (7)$$

where $C_{cf} \approx (\varepsilon_o a/h)(b - |X_2 - y|)$, when recast in terms of the state variable X_2 and the input variable y . These state equations are represented in the block diagram shown in Fig. 3 and solved numerically using SIMULINK. The charge Q (state variable X_1) is obtained as the output of the integration unit shown in the upper part of the block diagram; the displacement x and the velocity dx/dt (respective state variables X_2 and X_3) are evaluated in the lower part of the same diagram.

B. Small-Amplitude Excitation and Linearization

For small-amplitude input oscillation δy about a static operating point, it is possible to obtain small-signal voltage δV_{em} and force δF_{e-x} by retaining only the first-order terms in the Taylor series expansions of (1) and (2)

$$\begin{aligned} \delta V_{em} &= \left. \frac{\partial V_{em}}{\partial Q} \right|_o \delta Q + \left. \frac{\partial V_{em}}{\partial x} \right|_o \delta x + \left. \frac{\partial V_{em}}{\partial y} \right|_o \delta y \\ &\approx \frac{1}{C_o} \delta Q + \text{sgn}(x_o - y_o) \frac{Q_o}{C_o^2} \frac{\varepsilon_o a}{h} \delta x \\ &\quad - \text{sgn}(x_o - y_o) \frac{Q_o}{C_o^2} \frac{\varepsilon_o a}{h} \delta y \\ &= \frac{1}{C_o} \delta Q + \text{sgn}(x_o - y_o) \frac{V_o}{b - |x_o - y_o|} \delta(x - y) \end{aligned} \quad (8)$$

$$\begin{aligned} \delta F_{e-x} &= \left. \frac{\partial F_{e-x}}{\partial Q} \right|_o \delta Q + \left. \frac{\partial F_{e-x}}{\partial x} \right|_o \delta x + \left. \frac{\partial F_{e-x}}{\partial y} \right|_o \delta y \\ &\approx \text{sgn}(x_o - y_o) \left(\frac{Q_o}{b - |x_o - y_o|} \right) \frac{1}{C_o} \delta Q \\ &\quad + \left(\frac{Q_o}{C_o} \frac{\varepsilon_o a}{h} \right) \frac{V_o}{b - |x_o - y_o|} \delta(x - y) \\ &= \text{sgn}(x_o - y_o) \frac{Q_o}{b - |x_o - y_o|} \delta V_{em} \end{aligned} \quad (9)$$

where x_o and y_o denote the static displacements of the resonator and the frame; $C_o \equiv (\varepsilon_o a/h)(b - |x_o - y_o|)$, $Q_o \equiv Q_f(C_o/(C_o + C_{fg}))$, and $V_o \equiv Q_o/C_o$ are the respective values of the capacitance of, the charge on, and the voltage across C_{cf} at the operating point. Notice that (8) and (9) do not apply when $x_o - y_o = 0$, in which case $\delta(x - y)$ must be substituted by its absolute value.

For $x_o - y_o > 0$, (3) and (4) can be linearized to yield

$$\begin{cases} M \frac{d^2 \delta x}{dt^2} + \beta \frac{d \delta x}{dt} - \left\{ k + \frac{Q_o V_o}{[b - (x_o - y_o)]^2} \right\} \delta(x - y) \\ \quad + \Gamma \delta V_{em} = 0, \\ R_L \left\{ \frac{d \delta Q}{dt} + C_L \frac{d}{dt} \left[\frac{\delta Q}{C_{fg}} + \frac{\delta Q + \Gamma \delta(x - y)}{C_o} \right] \right\} \\ \quad + \left[\frac{\delta Q}{C_{fg}} + \frac{\delta Q + \Gamma \delta(x - y)}{C_o} \right] = 0 \end{cases} \quad (10)$$

where the transformer factor $\Gamma \equiv \delta F_{e-x}/\delta V_{em} = Q_o/(b - (x_o - y_o))$. It can be seen that the coupling field behaves like a spring with a *positive* spring constant $k_e \equiv Q_o V_o/[b - (x_o - y_o)]^2$.

Based on (10), a linear equivalent circuit (Fig. 4) can be constructed. The electrical and the mechanical subcircuits are linked by an ideal transformer with a transformer factor Γ . The resulting linear circuit can be Fourier transformed to yield the spectrum $P(\omega)$ of the power P dissipated in R_L as shown in (11) at the bottom of the page, where $\omega_e \equiv 1/R_L(C_{fg}C_o/(C_{fg} + C_o))$ is the characteristic electrical angular frequency, $\omega_m = \sqrt{(k^* + Z_m)/M}$ is the natural mechanical angular frequency, $k^* \equiv k + k_e$ is the total equivalent spring constant, $Z_m \equiv \Gamma^2[(R_L/(1/j\omega C_L) + (1/j\omega C_{fg}))/(1/j\omega C_o)]$ is the

$$P(\omega) = \frac{\frac{\omega^2}{\omega_e^2} \frac{\Gamma^2 Y^2}{R_L C_o^2} \left(\frac{\omega^4}{\omega_m^4} + 4\zeta^2 \frac{\omega^2}{\omega_m^2} \right)}{\left(1 - \frac{\omega^2}{\omega_m^2} - 2\zeta \frac{\omega^2}{\omega_e \omega_m} \right)^2 + \frac{\omega^2}{\omega_e^2} \left[\left(1 - \frac{\omega^2}{\omega_m^2} \right) (1 + \omega_e R_L C_L) + 2\zeta \frac{\omega_e}{\omega_m} \right]^2} \quad (11)$$

Fig. 5. Dependence of the effective spring constant k_e and the transformer factor Γ on $|x_o - y_o|$.

Fig. 6. Simulated dependence of the power output and the resonator displacement on y_M .

mechanical impedance induced by the electrical subcircuit, and $\zeta = \beta/2M\omega_m$ is the damping ratio of the system.

III. SIMULATION

The values of the elements used in the models are evaluated using the appropriate material properties and the device dimensions shown in Fig. 1. The estimated values of M and k of the mechanical resonator are 2×10^{-7} kg and 138 kg/s² [8], respectively. Consequently, the purely mechanical natural vibration frequency $(1/2\pi)\sqrt{k/M}$ according to the linear model is ~ 4 kHz. Based on the area of the movable capacitor plate, a value of ~ 1 pF for C_{fg} and a value of ~ 1.9 pF for C_{cf_max} are estimated. For a net stored charge Q_f of ~ 8 μ C/m², the variation of k_e and Γ as a function of $|x_o - y_o|$ is plotted in Fig. 5. Note that k_e is two to three orders of magnitude smaller than the mechanical k for $y_M < 10$ μ m; hence it has negligible influence on the mechanical natural vibration frequency in this range.

With a sinusoidal driving frequency f of 4.2 kHz and amplitude y_M ranging from 1 to 2.5 μ m, P dissipated on $R_L = 62$ M Ω is obtained analytically using the set of linear model

(a)

(b)

Fig. 7. (a) Frequency spectrum and (b) waveform of the current response of a 5×4 array. $y_M = 1$ μ m.

(10) and numerically using SIMULINK for the set of nonlinear model (3) and (4). For $y_M \leq \sim 1.3$ μ m, the good overlap between the linear and nonlinear response shown in Fig. 6 is an indication that the device behaves essentially linearly in this range.

For $y_M = 1$ μ m, the spectral density [Fig. 7(a)] of the waveform [Fig. 7(b)] of the current i_L flowing across R_L contains substantially only one component at the driving frequency, as expected for a linear system. Consequently, (11) is applied to study the dependence Fig. 8 of P on R_L and f at $y_M = 1$ μ m. Clearly, P is maximum at $f \sim 4.2$ kHz, close to the natural vibration frequency of 4 kHz. P is the largest at $R_L = 62$ and 3.2 M Ω , respectively, for $C_L = 0$ and 16.8 pF. The latter consists of a contribution of ~ 14.8 pF from the way the device is laid out and a further contribution of ~ 2 pF from the measurement setup.

Nonlinearity appears gradually when y_M is increased beyond 1 μ m. At $y_M = 7$ μ m, an obvious distortion in the current waveform Fig. 9(a) is observed, caused by the appearance of

Fig. 8. Dependence of the power output of a 5×4 array on driving frequency, resistance load, and parasitic capacitance calculating using the linear model. $y_M = 0.1 \mu\text{m}$.

Fig. 9. (a) Waveform and (b) frequency spectrum of the current response of a 5×4 array. $y_M = 7 \mu\text{m}$.

the second- and higher order harmonics in the corresponding frequency spectrum Fig. 9(b).

Fig. 10. Schematic cross-sections of the microgenerator after (a) the formation of the insulated floating electrode and (b) release of the resonator. (c) A secondary-electron micrograph of a fabricated 5×4 array generator.

IV. FABRICATION

The technology Fig. 10 developed to fabricate the microgenerator consists of a conventional CMOS “front end” process to realize the floating electrode, the sense transistors, and the other electronic devices, as well as a compatible low-temperature “back end” process to realize the resonator.

Fig. 11. Current–voltage characteristics of a tunnel oxide before and after breakdown.

The front-end process started with conventional n-type silicon substrates Fig. 10(a). The active areas were defined using a “LOCOS” isolation process, using low-pressure chemical vapor deposited (LPCVD) stoichiometric silicon nitride as the oxidation mask. A layer of sacrificial poly-Si was added to induce a subsequent large-area etching of the underlying silicon substrate to form a buried air cavity. LPCVD low-temperature oxide (LTO) was used as a diffusion mask, and heavily phosphorus-doped regions were created to form the tunneling and substrate contacts. A thin thermal oxide, 20 nm, was formed as the “charging” tunnel oxide and the transistor gate oxide. A heavily doped poly-Si is sandwiched between two layers of LPCVD low-stress silicon nitride. This poly-Si forms the floating electrode common to both C_{cf} and C_{fg} , as well as the gate of the sense transistor. After contact hole opening, the interconnects were realized using a double-layer of titanium/tungsten and gold (Au).

For the back-end resonator process [Fig. 10(b)], a first layer of 0.5 μm aluminum (Al) was sputtered and patterned to form the “anti-stiction” standoff bumps. This was combined with a second layer of 2 μm Al to form the sacrificial layer and the conductive base layer to provide the current path needed for electroplating on the isolated seed layers. The windows on which the resonator would be anchored were opened. A 30 nm/100 nm titanium:tungsten/Au adhesion/seed layer was sputtered and patterned using a liftoff technique. The resonator was then formed by Clariant AZ 4903 photoresist molded Au electroplating. Au was plated in a commercial Neutronex 309 solution at 50 $^{\circ}\text{C}$. The respective thickness of the photoresist mold and the structural Au was 40 and 36 μm . After the plating, all sacrificial layers were removed and the buried air cavity was formed in one immersion in a heated solution of tetramethylammonium hydroxide. A fabricated 5×4 array generator is shown in Fig. 10(c).

V. CHARACTERIZATION

The tunnel oxide was characterized using an HP4145B semiconductor parameter analyzer. Typical current–voltage characteristics before and after electrical breakdown are shown in Fig. 11. The respective turn-on voltage needed to initiate

Fig. 12. Dependence of the floating electrode voltage V_f on the control gate voltage V_c .

Fowler–Nordheim tunneling and the breakdown voltage are 12 and 19 V, relative to an electrically grounded substrate. These define the operating range of the floating-electrode voltage V_f at the beginning of the charging process. If $x_o - y_o = 0$ during the charging process, then V_f is related to the voltage V_c applied on the externally accessible “control gate” (i.e., the resonator) through the “coupling ratio” $\eta \equiv C_{cf_max} / (C_{cf_max} + C_{fg})$ and the injected charge Q_f by

$$V_f = \eta V_c + \frac{Q_f}{C_{cf_max} + C_{fg}} \quad (12)$$

where η was experimentally determined to be ~ 0.6 (Fig. 12). Since $Q_f = 0$ prior to the charging process, a range between 20–30 V was determined for V_c . Furthermore, since electrons are the tunneling species during the charging process, $Q_f < 0$ and V_f decreases with continued charging. Charging stops when V_f is reduced to the tunneling threshold of ~ 12 V.

Charging of the floating electrode was accomplished by the application of a series of voltage pulses to the control gate, with an amplitude of 25 V (corresponding to an initial V_f of ~ 15 V) and a duration of 3 ms. The charging process can be monitored by measuring the shift in the threshold voltage of the sense transistor, the gate of which is connected to the floating electrode. Since $Q_f < 0$, a positive shift is expected. This is clearly observed in Fig. 13. If V_f were reduced to 12 V such that the floating electrode were fully charged, Q_f would be $\sim 19.2 \mu\text{C}/\text{m}^2$.

Power generation was characterized by mounting the micro-generator on an MB Dynamics Model BM 25 A shaker as a vibration source. With the shaker vibrating at an amplitude of 2.2 μm , the frequency dependence (Fig. 14) of the voltage waveform generated across an $R_L = 10 \text{ M}\Omega$ is monitored. A maximum output power of 16 nW is obtained with the shaker vibrating at 4.2 kHz, close to the designed mechanical natural frequency. The corresponding voltage waveform is shown in Fig. 15.

Stronger nonlinearity set in and distortion in the waveform (Fig. 16) appeared when the vibration amplitude of the shaker

Fig. 13. Evolution of the transfer characteristics of a sensing transistor after a series of electron injection pulses.

Fig. 14. Dependence of measured power output on the driving frequency.

Fig. 15. Voltage waveform of a generator driven at its natural vibration frequency.

was increased to $3.2 \mu\text{m}$. This distortion is a reflection of the inherent nonlinearity of the system, as described earlier.

Fig. 16. Voltage waveform of a generator driven at $y_M = 3.2 \mu\text{m}$.

Fig. 17. Power output dependence on resistance load R_L .

With the shaker vibrating at an amplitude of $2.2 \mu\text{m}$ and close to the mechanical natural vibration frequency of the microresonator, the dependence of the output power on R_L is shown in Fig. 17. A maximum power of 65 nW is obtained at an $R_L = 50 \text{ M}\Omega$, corresponding well to that simulated at the estimated $C_L \approx 16.8 \text{ pF}$. The dispersion is larger for the measured than for the simulated power output. A possible cause of such underestimation is the simplifying assumption of lumping the distributed geometry of the resonator as a “point” mass in the model equations, thus ignoring its internal dissipation and delay.

Compared to the first and third devices in Table I, the presently proposed single-wafer generator is smaller and requires no macroassembly. Compared to the second device with a microfabricated resonator and a small capacitor gap space of $2.2 \mu\text{m}$, the presently proposed generator resonates at a frequency with roughly the same order of magnitude. Naturally, the actual working frequency must be tuned to each specific application.

VI. CONCLUSION

A *single-wafer* floating-electrode electrostatic electric microgenerator, integrating electronic devices for “charging” and rectification, was modeled, designed, fabricated, and characterized. Based on the electromechanical interaction through a coupling electrostatic field, a general physical model expressed in terms of a set of nonlinear coupled differential equations describing the dynamic behavior of the microgenerator was developed. For small-amplitude excitation, a circuit network based on a set of linearized equations is developed. The generator is realized using a compatible combination of standard CMOS floating-gate process and a post-CMOS photoresist molded electroplating process. Adequate agreement between model predictions and measurement results was obtained.

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