Power Processing Issues for Micro-Power Electrostatic Generators

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Abstract - For various monitoring and sensing applications it is desirable to power the electronics by scavenging energy from any locally available source. A prototype generator for low frequency (human body) motion has been developed using a micro-machined (MEMS) implementation of an inertial generator based on a moving-plate capacitor. The prototype generates pulses of 300 V on a 10 pF capacitor. This paper examines the design of a circuit and mosfet device to convert this energy to a low voltage. Because of the very small charge involved, the effect of leakage and parasitic stored charge are important. A silicon-on-insulator design is proposed and is examined through physics based finite-element simulation. The overall effectiveness of the generation process is shown to be composed of several terms which are functions of system parameters such as generator flight time, device area and circuit inductance. It is shown that device area is a compromise between leakage current, charge storage and on-state voltage. It can, for a given generator and inductance, be optimised to provide the maximum energy yield.

I. INTRODUCTION

Increasing miniaturization and cost reduction of sensors, circuits and wireless communication systems is creating a technology that widely distributes electronic sensors and data processing and uses wireless communication between these elements. For instance, a patient might wear temperature and blood gas monitors that transmit data during the course of his/her normal activity. Each sensor and transmitter will require a power supply, and for those worn on, or implanted into, the human body it is desirable to avoid trailing wires and the need to replace batteries. Provided that the power consumption of the signal electronics is low, the power can be scavenged from the environment. A promising technology is to use natural body movement to generate electricity. A variety of micro-machined vibration-driven generators are under development employing electrostatic [1], electromagnetic [2], or piezoelectric phenomena [3] to convert the kinetic energy of a suspended mass into electrical energy. The aim is to achieve a complete miniature on-chip power supply whose manufacturing process is compatible with semiconductor batch fabrication. To date, little has been reported on power conversion electronics for micro-generators.

II. THE PARAMETRIC ELECTROSTATIC GENERATOR

The generator considered here is of a non-resonant capacitive type (or ‘parametric’ [4]). The moving mass does not have a spring suspension, and therefore can be stimulated from low-frequency, irregular movement such as human body motion. Resonant devices, by contrast, suit high-frequency, regular, small amplitude vibration. A prototype generator [5] of the type investigated is shown in Figure 1.

![Prototype generator (active area 12×10 mm).](image1)

The capacitor is formed by one electrode which is weighted and free to move, as shown in Figure 2, and by a second electrode which is stationary relative to the chip.

![Exploded view of generator under development.](image2)

To initiate a generation cycle, the capacitor is pre-charged to a low voltage $V_1$. Accelerating the device causes the weighted electrode to move against the attractive force between the electrodes, thereby increasing the potential energy in the system. If the charge $q$ is held constant, the capacitor voltage increases, and the increase in potential energy is given by

$$ E = \frac{1}{2}q(V_2 - V_1) $$

where $V_2$ is the finishing voltage. Substituting the standard relationships for parallel plate capacitors yields the
generated energy in terms of the change in plate separation, \( x \), and the finishing voltage. It is clear that to obtain a good energy yield it is beneficial to arrange for a high final voltage on the capacitor plates.

\[
E = \frac{1}{2} V^2 \frac{\Delta A}{x_2} \left(1 - \frac{x_1}{x_2}\right) \quad \text{or} \quad E = \frac{1}{2} V^2 \frac{C_2}{C_1} (C_1 - C_2)
\]

The generating cycle can be divided into five phases as illustrated by Figure 3. The generator starts from the position where the two electrodes are at their closest.

In Phase 2, the capacitor is pre-charged. The prototype device has a capacitance of around 140 pF during Phases 1 and 2, and a 30 V supply places a charge of approximately 4.2 nC onto the electrodes. In Phase 3, the charging circuit is detached from the moving electrode and the device is primed and ready to generate. When the movement of the device reaches the point where the acceleration \( x \) of the moving electrode exceeds the attractive electrostatic force between the electrodes, Phase 4 is initiated and the plates begin to separate under constant charge conditions.

At full separation the capacitance drops to approximately 10 pF (see measured waveforms in Figure 4), and the voltage rises to 250 V. The presence of parasitic capacitance prevents the theoretical voltage of 420 V being obtained. The converter can now be turned on to initiate Phase 5, during which the generated energy is processed. Achieving a higher starting capacitance will allow the pre-charge and finishing voltages to be reduced.

### III. POWER PROCESSING

The method considered here uses a power converter circuit to remove the charge from the capacitor and to convert the energy to a useful voltage of, say, 3 V.

An important consideration is that the converter should not adversely affect the operation of the generator in the earlier phases. Specifically, the circuit should not significantly leak current during the flight of the moving plate or present a large parasitic capacitance that absorbs charge from the generator during the flight.

A suitable power conversion circuit is the half-bridge step-down circuit shown in Figure 5. The half-bridge has been chosen so that a boot-strap drive can be used to switch the high-side mosfet. Although the generation cycle time is long (circa 1s) and unpredictable, the power converter need only operate for less than 1µs to completely discharge the capacitor and so the boot-strap technique is viable. It is proposed to use the circuit in single-shot mode. It is desirable to use an integrated inductor, and inductance values in the range 1-10 µH appear to be achievable [6,7]. The discharge of the generator will occur in a short current pulse and controlling this current through chopping would require a high switching frequency and associated losses. Currents of the order of 0.1-1 A are expected over periods of up to 1µs.

As a first step to designing the circuit, an assessment was made of the input resistance and capacitance that the circuit must present in the off-state at the maximum generator voltage in order not to compromise generation. The generator’s electro-mechanical system was simulated numerically for a range of static impedances on the generator outputs using Matlab, assuming a 20 ms flight time. Figure 6 shows that the requirements are unusually strict: to maintain 80% of the generated energy the off-state loading should be more than 10^{12} \( \Omega \) and less than 1 pF. These values are not available with standard discrete mosfets rated for 300 V blocking.
To achieve the very high insulation levels required, a thin-layer silicon-on-insulator (SOI) mosfet design [8] has been chosen. This technology is compatible with MEMS and integrated circuit processing. The focus within this aspect of the system is to design a device with the appropriate leakage and parasitic capacitance and the ability to conduct the necessary on-state current with low power loss. A key parameter is the effective area of the device. In this study a circular cell was designed of radius 70 µm, as shown in Figure 7, and larger effective areas were obtained through parallel connection of cells.

IV. SYSTEM EFFECTIVENESS

The operation of the generator system is subject to a number of power loss terms and there are several variables that can be adjusted to optimise the power yield. Several of the factors are related and there are competing factors that need to be traded off against each other. These will be introduced in brief before a more detailed discussion of the design is presented.

A. Mechanical effectiveness

The issue with the mechanical system is not so much efficiency but the effectiveness in coupling energy from the motion into work done against the electrostatic force. The maximum attainable power density is strongly influenced by the generator architecture and conversion strategy, e.g., operating in constant voltage mode or constant charge mode or making use of mechanical resonance. However, for a given architecture, generator dimensions, and motion of the generator frame, the mechanical efficiency is solely a function of the electrostatic force [4]. In the constant charge case discussed here, this force can be controlled by setting the pre-charge voltage.

The conversion circuit should set the pre-charge voltage to a value corresponding to an electrostatic force which maximises the force-distance product. Too high a voltage (and force) and the plate will fail to move or will not travel the full distance. Too low a voltage (and force) and the opportunity to generate against a higher force is lost. The optimal force allows the plate to break free close to the point of maximum acceleration. The mechanical effectiveness is the ratio of energy coupled per stroke to the maximum that could have been achieved.

\[ \eta_{\text{mech}} = \frac{W_{\text{field}}}{W_{\text{field}}} \]

B. Generation efficiency

During the generation phase the plates of the capacitor should be opened under constant charge conditions. Two factors mean that this is not achieved in practice. There will be a leakage of charge through conductance paths which, in the system considered here, is principally leakage through the mosfets of the power converter circuit. The second factor is displacement of charge from the generator (as its voltage increases) into any parasitic capacitance. There will be parasitic capacitances in the generator structure itself but also in the mosfets of the converter. Within these devices capacitances occur at semiconductor junctions and between conducting layers including the carrier wafer. Both of these factors point to the need to use low-area mosfets in order to maintain a high effectiveness in generation. Leakage and charge sharing directly affect the energy that can be recovered from the generator during the discharge phase but also have a further indirect effect in modifying the flight of the moving plate, thus altering the mechanical effectiveness.

The generation efficiency is given by

\[ \eta_{\text{gen}} = \frac{E_{\text{gen}}}{W_{\text{field}}} = \frac{E_{\text{gen}} - E_{\text{stored}}}{W_{\text{field}}} \]

where \( E_{\text{gen}} \) is the increase in energy in the generator.

C. Conversion efficiency

The circuit used to discharge the generator and form the low voltage output will have various power losses which include the loss in the mosfet and diode, conduction loss in the inductor and the power consumed in the gate drive of the mosfet. We can define the conversion efficiency as

\[ \eta_{\text{conv}} = \frac{E_{\text{out}}}{E_{\text{gen}}} \]

For the mode of operation chosen here it is not helpful to...
separate the mosfet losses into conduction and switching loss. Increasing the cross-sectional area of the mosfet will decrease conduction loss and avoid saturation, but is counter to the requirements for high generation efficiency. The area also affects the gate drive requirement. The mosfet losses are also affected by the choice of inductor because this sets the amplitude and duration of the discharge current. Increasing the cross-section of the low-side mosfet increases the charge withdrawn from the generator in order to reverse bias the diode, at the point when the high-side mosfet is switched on.

D. System effectiveness

The various factors can be combined together to form an overall effectiveness of the system as follows,

$$\eta_{\text{eff}} = \eta_{\text{mech}} \times \eta_{\text{gen}} \times \eta_{\text{conv}}$$

The dominating factors are expected to be as shown in Table 1.

<table>
<thead>
<tr>
<th>Dominant factors</th>
<th>$\eta_{\text{mech}}$</th>
<th>$\eta_{\text{gen}}$</th>
<th>$\eta_{\text{conv}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-charge voltage $V_{\text{pre}}$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame motion $Y(t)$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flight time $t_{\text{flight}}$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Device area (cell number) $n_{\text{cells}}$</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Max. operating Voltage $V_{\text{max}}$</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Converter inductance $L$</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Length of mosfet’s drift region</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Carrier lifetimes $t_n, t_p$</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Device gate area $A_{\text{gate}}$</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 1: Dominant factors influencing mechanical effectiveness, generation efficiency and conversion efficiency.

The mechanical effectiveness is mainly a function of the pre-charge voltage and system motion. Drift region length and carrier lifetime influence leakage and, in turn, the conversion efficiency. These effects illustrate the dependency on the devices’ voltage ratings, and on their on-and off-state impedances.

The task is to maximise the energy that can be extracted from the mechanical source and delivered to the low voltage supply. The optimisation of the mechanical aspects have been previously reported [4]. The work reported here concentrates on designing a power converter circuit, including designing its mosfets (and reverse diodes), such that they maximise the generation and conversion efficiency and do not significantly degrade the mechanical effectiveness.

E. System simulation

Simulation of the converter circuit requires detailed models of the semiconductors which account for the charge flows in the devices and in the substrate wafer. Simulations were performed using Silvaco software in mixed-mode to incorporate finite element (FE) models of the mosfets, including the reverse diodes, into the remainder of the circuit. The FE models account for physical effects such as electron-hole-pair generation and impact ionisation (leakage currents), substrate currents (important for the high-side devices integrated onto grounded substrates), charge storage, and for carrier life-times corresponding to non-irradiated epitaxial silicon. Combining FE level simulation of the semiconductors with the mechanical simulation was not judged necessary at this stage. Separate simulations were performed with the generator capacitor in its closed and open position in order to assess the charge sharing effects.

V. DESIGN AND OPTIMISATION

A. Charge leakage

In the context of micro-generators, the main advantages of silicon-on-insulator devices are their high insulation and low parasitics, and the compatibility with MEMS and integrated circuit processing. The mosfet cell shown in Figure 7 was designed to block 300 V and carry a current of 1 mA. The output characteristics of one cell, equivalent to an active area of 0.015 mm$^2$, are shown in Figure 8. For gate voltages above 3 V the desired forward current lies in the mosfet’s ohmic region. In the off state (for gate voltages below 2 V) the high voltage on the mosfet causes carrier-pair generation and therefore a voltage and active area dependent leakage current. The carrier lifetime for the FE models was chosen to be 1µs which is typical for power mosfets. At room temperature and 300 V, a single cell conducts a leakage current of 98 pA. Resistive leakage occurs during the phases where the voltage is high and in an exponential fashion; the leakage current doubles from 250 V to 300 V.

Figure 8: Output characteristics obtained from the mosfet’s FE model for one cell (0.015 mm$^2$).

The charge lost to leakage depends on the duration of the flight of the moving capacitor plate and any delay between the open position being attained and the discharge being initiated. The portion of the flight for which the voltage exceeds 250 V is of most importance. This time depends
mainly on the nature of the motion, and it is usually below 10 ms for walking-induced motion. The discharge process occurs too fast for resistive leakage during this phase to become significant. As an estimate, each cell leaks 98 pA over 10 ms which corresponds to 0.98 pC. The charge loss scales with the number of cells employed. For a 100-cell (100 mA) mosfet the equivalent charge loss is 98 pC. The prototype generator was designed for an initial charge of 4.2 nC. The 98 pC thus contributes a 2% loss to the generation efficiency $\eta_{gen}$.

B. Charge sharing during generation

As the voltage rises across the moving plate capacitor the voltage also rises across the mosfet of the converter circuit and some of the charge stored on the capacitor will be displaced into the mosfet. The degree of dynamic charge sharing depends, in part, on the charge required to deplete the mosfet to achieve voltage blocking. This is not a linear effect: the depletion region capacitance decreases rapidly with rising voltage.

![Figure 9: Voltage-charge characteristics of the generator (open and closed) with and without conversion circuitry.](image)

Figure 9 shows the expected form of the voltage-charge characteristic for three situations: the generator capacitor in the closed (pre-charge) position, the capacitor in the open position without its converter circuit, and the capacitor in its open position with the converter. These simulated curves were generated by plotting the voltage rise associated with current (or charge) being injected into the respective systems. The graph allows the influence of the converter on generation to be estimated. The areas under these curves represent stored energy. The area bordered by the open-capacitor and close-capacitor curves and a line of constant charge represents the energy conversion from mechanical to electrical form for a flight at constant charge. The portion shown as stored in the power converter will be dissipated within the mosfet when the mosfet turns on and only the portion stored in the capacitor is available to be converted to useful output. By comparing the curves for the open capacitor with and without the power converter circuitry, it is seen that a larger charge (greater pre-charge voltage) is required to achieve a given finishing voltage and the energy available as useful output is reduced. The higher pre-charge voltage will alter the trajectory of the flight and will have an influence on the mechanical effectiveness of the generator. The figure also shows how the constant charge trajectory would be modified by charge leakage during the flight.

The charge displaced into the mosfet depends on the maximum voltage applied to the mosfet, the detailed design of the mosfet cell and the number of cells used. An exact voltage-charge profile was found through a mixed-mode FE simulation of the charging of the capacitor and converter. The results are shown in Figure 10 for numbers of cells between 6 and 100 (corresponding to mosfets designed for 6-100 mA). At 100 cells there is a significant displacement of charge into the mosfet but below 30 cells the displacement does not greatly affect the recoverable charge.

![Figure 10: Voltage-charge characteristics of the generator with the converter circuit attached. Results shown for mosfet sizes ranging from 6 to 100 cells.](image)

C. Conversion efficiency trade-offs

Mixed-mode circuit/FE simulation was also used to assess the efficiency of the converter in converting the stored energy at high voltage to a 3 V output. The circuit was that given in Figure 5 and the simulation was performed for a range of inductor values and a range of numbers of mosfet cells. The generator was modelled as a 10 pF capacitor charged to 300 V. The mosfet was turned on 10 ns into the simulation with a 3 V signal driving through a 10 $\Omega$ gate resistor.

The waveforms in Figure 11 show example waveforms for the discharge process. This example used 30-cell devices and a 10 $\mu$H inductor. For these parameters the discharge is approximately 40% efficient and several of the non-ideal effects are clearly visible. At turn-on the inductor voltage (which is also the high-side mosfet source voltage) swings upwards to meet the generator voltage (also the mosfet drain voltage). At the same time, the mosfet experiences a current
surge as currents flow to reverse bias the low-side diode. This causes a loss of generator charge as seen in the generator voltage dropping rapidly from 300 to 260 V. Once the charge has been redistributed, the mosfet current drops off only to rise again as the inductor voltage begins to accelerate the current through the 10 µH inductor. In this particular situation the mosfet saturated before the generator charge had been fully extracted, which can be seen by the voltage drop across the device increasing to almost 50 V. Increasing the active area of the device brings the drain and source voltage waveforms together, thereby increasing the efficiency during the latter phase of the conversion cycle. However the initial voltage drop is larger due to the larger current required to charge the diode, and the voltage time integral on the inductor is reduced, lowering the efficiency. Larger inductors increase the efficiency by extending the pulse duration and decreasing the peak inductor and mosfet current, thus avoiding the mosfet’s on-state losses. Note that the peak substrate currents are nearly as high as the peak drain currents.

Figure 11: Conversion waveforms showing effects which are considered during optimisation. Top: Generator, inductor and output capacitor voltage. Bottom: Inductor current and high-side mosfet terminal currents.

Results for a range of cell number and inductor values are summarised in Figure 12. It can be seen that from the case of Figure 11 (30 cells, 10 µH) the efficiency could be improved by either increasing the inductor value or increasing the number of cells. Larger inductors increase the efficiency by extending the pulse duration and decreasing the peak inductor and mosfet current, thus avoiding the mosfet’s on-state losses. Note that the peak substrate currents are nearly as high as the peak drain currents.

Figure 12: Summarised simulated conversion results showing efficiency for various inductors and device areas.

Beyond this number the power losses due to the increased charge sharing during generation and diode reverse biasing current during conversion outweigh the benefits of increased conduction efficiency. It must also be noted that increasing the number of cells beyond 30 starts to have a significant impact on the effectiveness of generation as revealed in Figure 10.

D. Gate drive power

The power dissipated in the gate and gate resistor is proportional to the device area and a weak function of the gate resistor. For the 30 cell device (0.45 mm²) referred to above, approximately 500 pJ are dissipated in the device and in the 10 Ω gate resistor per switching event. Increasing the gate resistor to 100 Ω reduces the gate drive energy to around 300 pJ. Switching frequencies of around 1 Hz are expected and this equates to a power of 0.3-0.5 nW.

There is an upper limit for the gate resistance. This is because the gate-substrate (not gate-body) capacitance needs to be charged as the device switches on and the source voltage swings up towards 300 V. The initial current surge is significant relative to the device size and must be taken into account for the device layout. If the mosfet’s gate resistance is not low enough, then the device remains in its saturated mode with the gate voltage measured directly on the device remaining at the gate-threshold voltage.

VI. DISCUSSION

Although the mosfet design could certainly be further optimised to improve overall efficiency, here we have focused on evaluating one system with particular parameters, so as to assess the impact of varying the active areas and inductor size. We can see that the generation efficiency decreases with increasing device size, while the conversion efficiency initially increases and then decreases, as the efficiency is dominated first by conduction and then by charge sharing losses. The optimum area for conversion efficiency increases with decreasing inductance, because
conduction losses become relatively more important. From Figure 10 and Figure 12 we can thus conclude that high inductance values are critical to achieving good circuit performance. Accordingly, the interesting regions of Figure 12 are to the left of the maxima, for example at 30 cells and 10 µH. Figure 10 shows that a conversion circuit using 30-cell devices does not significantly harm generation. It should also be mentioned that the parasitic capacitance of the inductors may have a significant impact, and this has yet to be analysed.

Leakage at the rated voltage is around 3 nA which would only become relevant for flight times in excess of 0.1 s. Despite the low charge levels, it is necessary to have good peak-current on-state performance and high voltage blocking; therefore, it appears that designing a specific power device more suitable for peak currents would allow the shrinking of generator and inductor sizes. The generator would then occupy less area on the chip which may be necessary for the technology to become viable.

It may also be beneficial to scale the high- and low-side mosfets individually, as the high- and low-side device areas affect generation and conversion efficiencies differently.

VII. CONCLUSIONS

Energy extraction from a micro-generator is feasible using modern mosfet technology scaled appropriately.

The electrostatic micro-generator is an application that sets unique constraints on the power electronics used to perform a step-down voltage conversion. The very small charge involved in each generation cycle requires very low off-state leakage impedances and small parasitic capacitances, but the devices are still required to conduct high peak currents, and block high voltages.

We have shown that a system using conventional silicon power devices is capable of extracting power from a relatively large capacitive micro-generator (> 1 cm²), using a 10 µH inductor.

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IX. REFERENCES


