Characterization the influences of diodes to piezoelectric energy harvester

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ABSTRACT

This study discloses the diode’s influences on the piezoelectric energy harvesting performance. The piezoelectric-based energy harvesting system plays an important role in scavenging environment vibration energy into electrical energy, which can be utilized by low-power electronic devices. With respect to the interface circuit, a full-wave bridge circuit is usually needed to rectify the alternating current (AC) signal into a direct current (DC) signal. The full-wave bridge is composed of four diodes, whose characteristics may influence the harvested power significantly. Therefore, in this paper, the diodes’ properties and influences on the energy harvesting performance are analyzed and presented via simulation and experimental studies. It is found the harvested energy has close relationship with the diode characteristics. For the high source impedance case, diode with low reverse leakage current is favorable. For the low source impedance case, diode with low forward voltage drop is favorable. The corresponding experimental study is carried out via a piezoelectric beam, which shows that the measured harvested power differences can almost be up to 800% for the same test structure.

1. Introduction

Piezoelectric energy harvesting devices provide feasible solutions for the vibration energy scavenge technique. The extracted vibration energy can be converted into electrical energy, which can be further provided to wireless sensors or low power consumption devices.

The piezoelectric-based energy harvesting system generally includes two parts, the mechanical design part and the interface circuit part. The purpose of mechanical design is to increase the harvester’s bandwidth, efficiency, and low frequency compatibility [1-4]. The purpose of the interface circuit is to rectify and condition the output voltage, and store and manage the electrical energy [5].

Figure 1 is a schematic diagram of a classical piezoelectric energy harvesting system. A cantilever beam is clamped to the base, which is under mechanical excitation. A piezoelectric patch is bonded near the beam’s clamped end, which can convert the
mechanical stain energy into electric energy via piezoelectric effect. As most low-power electronic devices require a constant DC supply, a full-wave bridge rectifier is usually essential, which rectifies the AC signal into DC signal. The rectified energy can be preserved at a capacitor $C_{rec}$, and is consumed by a load, which is simplified as a resistor $R$.

The classical interface is simple and passive in nature, although it suffers relatively low efficiency drawbacks. Several improved interface circuits have been consequently proposed. However, it should be noted that the full-wave bridge remains as an essential part of many advanced interface circuits, such as synchronized switch harvesting on inductor (SSHl) [6], synchronous electrical charge extraction (SECE) [7], and enhanced synchronized switching harvesting (ESSH) [8] types. As one representative case, the schematic diagrams of Parallel-SSHl and Series-SSHl interface circuits are given in Figure 2.
When the full-wave bridge circuit begins to work, the generated voltage needs to overcome the diode’s barrier potential before it reaches the output terminals. Meanwhile, there may exist other parameters, which could influence the final output power.

In this study, a systematic study is carried out to reveal the importance of diode selection to the piezoelectric energy harvesting performance, which has not been put sufficient attention from the previous literatures. The diode’s characteristics are depicted via simulation and experimental approaches. The obtained results are summarized and compared. Finally, the energy harvesting performances are compared via a realistic piezoelectric energy harvester and the optimum diode for the maximum energy harvesting performance is determined.

2. Diode losses analysis

The diode can be modeled using the offset-resistance model [9], which is shown in Figure 3.

At the forward bias status, the diode can be represented by a barrier potential in series with a low forward resistance $R_{on}$. Therefore, the diode’s on-state loss is occurred when large forward current $I_F$ is flown in the circuit. At the blocking reverse bias status, the diode can be represented by an open break in parallel with a large reverse resistance $R_{off}$. Therefore, the diode’s blocking loss is generated as small reverse leakage current $I_{Rev}$ existing in the circuit. The two status are taken in turn via switching, which corresponds to the diode’s switching loss.

The diode’s on-state loss can be calculated as:

$$P_{on} = V_B \times I_{F(avg)} + R_{on} \times I_{F(RMS)}^2$$

As the $R_{on}$ value is very small, the diode’s on-state loss is mainly determined by the barrier potential $V_B$. A low barrier potential is vital to minimize the diode’s on-state loss.

The blocking loss has close relationship with the reverse leakage current, which can be calculated as:

$$P_{block} = R_{off} \times I_{Rev(RMS)}^2$$

Figure 3. Diode offset-resistance model.
The blocking loss is usually taken into consideration with respect to Schottky type diode, which has larger reverse leakage current than the Silicon type diode. In general, the Schottky type diode has smaller barrier potential than the Silicon type. To decrease the barrier potential, the Schottky barrier height should be reduced, which has linear relationship with the barrier potential. However, the reverse leakage current can be exponentially increased simultaneously [10], which increases its blocking loss. A proper balance should be made between reverse leakage current and the barrier potential.

The switching loss is in proportion with the switching frequency. In the mechanical energy harvesting applications, the interesting frequency is usually low, which makes the switching loss can be neglected.

For the piezoelectric-based energy harvester, it is generally only consider the diode’s forward value. However, as the above analysis and suggestions [11] have been presented, the reverse leakage current also influences the output power. The reason is during the full-wave rectification process, there are only two diodes working in the forward mode, whereas the other two diodes are working in the reverse mode. Consequently, the diodes in reverse mode can form a leakage current path, which may degrade the energy harvesting system’s performance. Therefore, it is interesting to look into different kinds of diode characteristics and benchmark their influences to the harvester’s output power value.

3. Diode characteristics via simulation study

Here, four different diodes are chosen for investigation: (1) 1N5817 Schottky diode; (2) 1N5711 Schottky diode; (3) 1N4148 Silicon diode; (4) 1N4001 Silicon diode;

Details of the four diode types are provided, which are shown in Table 1.

As each diode’s characteristics are different, it is sensible to evaluate the diode’s influence through numerical simulation initially. To fulfill this task, NI Multisim™ software is utilized in the simulation study.

3.1. Diode forward voltage drop test

A virtual Agilent 34401A Multimeter is built in the Multisim™ software, its diode test function is employed to measure the diode forward voltage drop value. The measured results are given in Table 2.

| Table 1. Selected diodes’ parameters.          | 1N5817 | 1N5711 | 1N4148 | 1N4001 |
|-----------------------------------------------|--------|--------|--------|--------|
| **Diode**                                     | Schottky | Schottky | Silicon | Silicon |
| **Type**                                      | 20V    | 70     | 100    | 50     |
| **Repetitive peak reverse voltage**           | 0.45V@1A | 0.41V@1mA | 1V@15mA | 1.1V@1A |
| **Forward Voltage drop(25°C)**                | Typical 12 μA | 0.2μA@50V | 25 nA | 5μA@50V |
| **Maximum DC reverse current (25°C)**         | @20V Max. 1mA@20V | 15mA | 300mA | 1A     |
| **Forward Continuous current(25°C)**         | 1A     | 15mA   | 300mA  | 1A     |
The simulation results show that the Schottky diode generates less voltage drop values than the Silicon type, and 1N5817 diode generates the lowest voltage drop value.

### 3.2. Diode reverse leakage simulation test

The diode’s reverse leakage current is usually weak, which makes direct current measurement becomes difficult. To obtain reliable reverse leakage current value, the test diode is connected with a 100 kΩ resistor in series. A DC power source is used to provide constant DC reverse voltage (10V) to the test circuit. The voltage on the resistor can be obtained via the virtual Agilent 34401A Multimeter and the reverse leakage current value is calculated according to Equation (3).

\[
I_{\text{Rev}} = \frac{V_R}{R}
\]  

(3)

where \(V_R\) is the measured voltage on the resistor, \(R\) is the resistor’s value in series.

The simulation circuits of the reverse leakage current test are shown in Figure 4, and the obtained values are given in Table 3.

The measured voltage on the resistor and the corresponding calculated reverse leakage current is shown in Table 3.

According to the simulation result, the 1N5817 diode’s reverse leakage current is several orders higher than other diode types. As the 1N5817’s reverse leakage current

| Diode   | \(\Delta V\) (mV), 1 mA |
|---------|-------------------------|
| 1N5817  | 126.74                  |
| 1N5711  | 387.07                  |
| 1N4148  | 597.15                  |
| 1N4001  | 535.45                  |

- **Table 2.** Diodes forward voltage drop values with 1 mA excitation.
value seems so large, experimental study is carried out to make further verification, which is presented in Section 4.

4. Diode characteristics via experimental study

4.1. Diode forward voltage drop test

Besides the previous mentioned diode types, here, an integrated chip LTC3588–1 is newly added in the experimental study. This chip is specially designed for energy harvesting application, and has been used in many energy harvesting studies [12, 13].

The chip’s internal block diagram is shown in Figure 5. According to its specification, this chip integrates a low-loss, full-wave bridge circuit. When the piezo transducer’s AC voltage signal is connected to the PZ1 and PZ2 terminals, the rectified voltage can be obtained at the V_{IN} terminal. The other parts of this chip, such as UVLO mode and buck controller functions, are not utilized in this study.

A NI PXI-4070 Digital Multimeter is used to fulfill the experimental test. This device can provide a constant current source with different levels to excite the diode, and the voltage drop of the diode under test can be read out on the NI-DMM soft front panel.

The schematic diagram of the forward voltage drop is shown in Figure 6(a), and the measured forward voltage drop values under different excitation current levels are given in Table 4.

![Full-wave bridge rectifier](image)

**Figure 5.** Block diagram of LTC 3588–1[14].
It should be mentioned that, with respect to the LTC 3588–1 test, the forward voltage drop test utilizes the PZ1 and \( V_{IN} \) terminals, which is approximately equivalent to one diode.

According to the measured results, the forward voltage drop values become larger with a larger excitation current value. It is also shown that 1N4148, 1N4001, and LTC 3588-1 generate close forward voltage drop values, and 1N5817 generates the lowest voltage drop value.

### 4.2. Diode reverse leakage current test

Like the simulation study, except for the forward voltage drop test, the diode reverse current characteristics are also investigated.

Similar to the previous simulation approach, the test diode is connected with a 100kΩ resistor (1% accuracy) in series. A Tektronix PWS2826 DC power supply module is used.
to provide constant DC reverse voltage to the test circuit. The voltage on the resistor is measured via the PXI-4070 and the reverse leakage current value can be calculated according to Equation (3).

The schematic diagram of the reverse voltage drop test is shown in Figure 6(b). The measured voltage values on the resistor and the calculated reverse leakage current values are given in Table 5.

According to Table 5, the reverse leakage current values of 1N5711, 1N4148 and 1N4001 are at the same level. The LTC3588-1 and 1N5817 generate large reverse leakage current. However, with respect to 1N5817, the measured value only accounts to 4.2% of the simulation result, which makes the 1N5817 SPICE parameters should be carefully examined.

4.3. Diode parameters updating

Among the SPICE parameters, the reverse saturation current $I_s$ is important, which determines the maximum reverse current value within the breakdown voltage.

In the Multisim™ 1N5817 SPICE parameters, the $I_s$ value is $19 \mu A$. This parameter value is compared with the 1N5817 SPICE model (Advanced Analysis enabled) in the PSpice™ software, which equals to $1.667 \mu A$. Comparing with the experimental measurement result and the diode’s datasheet [15] (Figure 7, 25°C working condition), it is found that the latter value is more accurate.

Therefore, it is confirmed that the $I_s$ parameter in the Multisim™ model has been overestimated. The 1N5817 SPICE parameters with different models are presented in Table 6. After the model updating, the updated forward voltage drop values with 1 mA excitation is 178 mV, which is only slightly larger than the original model.

5. Piezoelectric energy harvesting via simulation study

After the model updating, the piezoelectric harvester can be setup, which is equivalent to an AC current source in parallel with a capacitor. After the rectification process, the stored energy of the external capacitor can be calculated as:

$$E = \frac{1}{2} CV^2$$  \hspace{1cm} (4)

where $C$ is the external capacitor’s capacitance, $V$ is the voltage across the it.

It should be noted that as the Schottky reverse resistance is smaller than the Silicon type, the obtained voltage value on the harvester’s output capacitor could be influenced by the harvester’s source impedance. Therefore, the following simulations present high source impedance and low source impedance cases respectively.

| Table 5. Measured voltage on the resistor and calculated reverse leakage current. |
|-----------------------------------------------|
| $V_R (mV)$ | 5 V | 10 V | 15V |
| 1N5817 | 44.4 | 83 | 126 |
| 1N5711 | 0.58 | 0.76 | 0.92 |
| 1N4148 | 0.46 | 0.56 | 0.62 |
| 1N4001 | 0.31 | 0.51 | 0.72 |
| LTC3588-1 | 63.7 | 120 | 140 |
| $I_{rev} (nA)$ | 5 V | 10 V | 15V |
| 1N5817 | 444 | 830 | 1260 |
| 1N5711 | 5.8 | 7.6 | 9.2 |
| 1N4148 | 4.6 | 5.6 | 6.2 |
| 1N4001 | 3.1 | 5.1 | 7.2 |
| LTC3588-1 | 637 | 1200 | 1400 |
Here, the 1N5817 SPICE model in Multisim™ has been modified according to the improved SPICE parameters in Table 6. The simulation result adopting the original 1N5817 Multisim™ model is also provided for comparison.

(1) High source impedance

The simulation graph is shown in Figure 8.

The corresponding source impedance can be calculated according to [16]:

$$R = \frac{1}{\omega C_p}$$  \hspace{1cm} (5)
Here, the resonant frequency is chosen as $\omega = 2 \times \pi \times 300 \text{ rad}$, inherent piezoelectric capacitance $C_p = 1 \text{ nF}$. Accordingly, the calculate source impedance equals to $R = 530.8 \text{k}\Omega$. This impedance is close to the source impedance from reference [11]. The measured voltage and calculated energy results are shown in Table 7.

Intuitively, if selecting the diode based on the forward drop values, 1N5817 diodes should achieve the best performance. However, the simulation results show that for an energy source with high impedance, the 1N4001 achieves better performance than 1N5817, which agrees with the experimental findings from reference [11]. The 1N5711’s performance is also satisfying, as its forward voltage drop is lower than 1N4001 and its reverse leakage current is only a little larger than 1N4001.

(2) Low source impedance

The simulation graph is shown in Figure 9. As $\omega = 2 \times \pi \times 300 \text{ rad}$, inherent piezoelectric capacitance $C_p = 100 \text{nF}$. The calculated source impedance equals to $R = 5.31 \text{k}\Omega$. This impedance is close to the source impedance of the experimental study in Section 6.

The measured voltage and calculated energy results are shown in Table 8.

The simulation results show that for an energy source with low source impedance, the 1N5817 diode, which has the lowest forward voltage drop value, achieves the best performance. Meanwhile, as using original Multisim™ model shows, if the reverse current is sufficiently large, the blocking loss will play more important role than the forward voltage drop parameter.

To validate the simulation findings, experimental study is further carried out, which is shown in Section 6.

|          | 1N5817(Updated model) | 1N5817(Multisim™ model) | 1N5711 | 1N4148 | 1N4001 |
|----------|-----------------------|-------------------------|--------|--------|--------|
| Voltage (V) | 0.07                  | 0.0002                  | 1.24   | 0.96   | 1.17   |
| Calculated energy(\(\mu J\)) | 0.08                  | \(\approx 0\)         | 25.37  | 15.21  | 22.59  |
6. Experimental study for piezoelectric energy harvesting

6.1. Experimental system setup for piezoelectric energy harvesting

As shown in Figure 10, a piezoelectric patch (type PZT-5H, 60 mm × 31 mm × 0.3 mm) is bonded to a copper beam (80 mm × 33 mm × 0.3 mm). The beam is fixed to an aluminum base. A PCB accelerometer (Type PCB 352a56, 100 mV/g) is mounted on the harvester’s clamped base, which is acquired via the PXI-4461’s AI channel for acceleration monitoring. A 20N shaker (Type HEV-20) is utilized to provide force excitation to the base. A LabVIEW-built signal generator provides band-limited white noise excitation signal (50 Hz-500 Hz) to the PXI-4461 module’s AO channel, which is sent to the shaker’s

Table 8. Measured voltage and calculated energy.

|                | 1N5817(Updated model) | 1N5817(Multisim\textsuperscript{TM} model) | 1N5711 | 1N4148 | 1N4001 |
|----------------|------------------------|------------------------------------------|--------|--------|--------|
| Voltage (V)    | 0.41                   | 0.23                                     | 0.31   | 0.002  | 0.24   |
| Calculated energy (µJ) | 2.77                   | 0.87                                     | 1.59   | 0.00007| 0.95   |

Figure 9. Circuit simulation with low source impedance.

Figure 10. Photograph of the piezoelectric cantilever beam and the shaker.
power amplifier. The piezoelectric patch’s voltage signal is measured by the PXI-6361 module’s AI channel.

The schematic diagram of the experimental test system is shown in Figure 11. When the test structure is excited, the power spectrum of the piezoelectric voltage signal can then be calculated, which is shown in Figure 12. The averaged mode is RMS averaging, the averaging time is 100, and the window type is Hanning.

As shown in Figure 12, at 299 Hz the vibration beam will generate a large resonance, which is selected as the target frequency for the following energy harvesting performance evaluation.

6.2. Diode’s influences to the stored energy

During the experimental test, the acceleration of the base is kept to be 0.1g at a 299 Hz frequency. The test structure is wired to a full-wave bridge circuit composed of different diode types. A 33 μF tantalum capacitor (AVX brand) is selected as the energy storage device. The tantalum capacitor has a remarkable smaller leakage loss than the electrolytic capacitor, which is suitable for the harvested energy conservation. The stored energy inside the capacitor is calculated according to Equation (4):

A picture view of these interface circuits under test is shown in Figure 13. The measured voltage values with different rectification diodes and the corresponding calculated energy values are given in Table 9. According to the measured results, the 1N5817 diodes-formed rectifier provides the largest energy conservation value, whereas the 1N4148 diodes formed rectifier provides the smallest energy conservation value.

6.3. Diode’s influences on the harvested power

Figure 14 gives the harvested power versus load resistance using different diode types, which shows that the harvested power performances can be significantly different for the same test structure.

![Figure 11. Schematic diagram of the experimental system.](image-url)
Figure 12. Measured voltage spectrum of the piezoelectric patch.

Figure 13. Assessment of diodes' influence on the harvested energy.

Table 9. Measured voltage and calculated energy.

|              | 1N5817 | 1N5711 | 1N4001 | 1N4148 | LTC3588-1 |
|--------------|--------|--------|--------|--------|-----------|
| Voltage (V)  | 1.10   | 0.88   | 0.54   | 0.50   | 0.55V     |
| Calculated energy(μJ) | 19.97 | 17.78 | 4.81  | 4.13   | 4.99      |
Here, the 1N5817 formed bridge gives the highest power value, which is 51.63 μW. Adopting the 1N4148 device gives the smallest power value, which is only 6.47 μW. The power values corresponding to 1N5711, 1N4001 and LTC 3588-1 are 29.32 μW, 8.59 μW and 9.44 μW, respectively.

Following the above experimental studies, it is confirmed that the previous simulation findings are reliable.

In addition, the measured result shows that the commercial LTC3588-1’s performance is not satisfying. Therefore, adopting the LTC3588-1 generates underestimated harvesting power performance. It’s also shown that the optimum resistance values for maximum power output are different with different diodes. This is caused by the internal resistance’s disparity with respect to different diode types.

7. Conclusions

In this article, the forward and reverse characteristics of different diodes (1N5817, 1N5711, 1N4001 and 1N4148) and the integrated chip LTC3588-1 have been investigated. The classical full-wave bridge composed of different diodes is used as the energy harvesting interface circuit, and the diode’s influence on piezoelectric energy harvester’s performance is presented via both simulation and experimental approaches.

With different diode types, the achieved energy harvesting performances can be significantly different, which are influenced by the diode’s forward voltage drop, reverse leakage current and the source impedance.

For the energy source with high source impedance, diode has small reverse leakage current parameter is favorable, which is more importantly than the forward voltage drop parameter.
For the energy source with low source impedance, and the reverse leakage current is within reasonable range, Schottky diode with low forward voltage drop parameter is favorable. As shown in the experimental result, adopting the 1N5817 diode achieves the best energy harvesting performance, which is almost 800% higher than the smallest case. It is also shown that adopting the LTC3588-1 device can underestimate energy harvesting system’s performance. To improve the output power, it is suggested the AC signal is rectified via 1N5817 formed full-wave bridge firstly, rather than via the LTC3588-1’s internal rectifier, then utilizes the needed functions provided from the chip for further application (UVLO, buck converter function, etc.).

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