ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

Investigation of the Heat Absorption Capacity of Silicon Schottky and PN Junctions

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ABSTRACT: The numerous advantages of using thermoelectric devices has led to continuous research to achieve their optimum coefficient of performance. Recently, some researchers in their publication presented schottky junctions as a very good heat absorbing device and developed a model for the heat absorption rate of this material. This work evaluated their postulation and found out that theoretically they are not wrong. However laboratory tests on sample diodes (1N5817, 1N5822, 1N5392 and 1N5408) indicated that their postulation cannot be realised by just biasing the diodes as they proposed. Both the schottky junctions (1N5817 and 1N5822) and PN junctions (1N5392 and 1N5408) failed to absorb heat in reverse bias mode, irrespective of the applied voltage. Rather they release heat upon breaking down. At voltages below reverse break down voltage, PN junctions appear not to absorb or release heat energy.

KEYWORDS: heat absorption, thermoelectric, schottky, Peltier, cooling.

I. INTRODUCTION

Presently in developing countries, cooling is mainly achieved for both domestic and industrial needs using vapour compressor and thermoelectric devices. Thermoelectric phenomena as described by Compton et al (2011) refers to the direct conversion of thermal energy into electricity or electricity into heat and vice versa by solid state devices. Thermoelectric phenomena can be applied in heating, cooling and electric power generation. Considering the fact that various efficient and cost effective heating technologies are readily available, researchers seems to have more interest towards applying this phenomena in cooling and electric power generation. In thermoelectric technology, cooling is achieved electronically according to Samar (2006) by using the "Peltier" effect to create a heat flux between the junctions of two different types of materials. Amandeep et al (2014) and Raghied (2011) described thermoelectric heat pump; which also known as Peltier module as solid-state active heat pump which transfers heat from one side of the device to the other with consumption of electrical energy, depending on the direction of the current. In the market, such an instrument is referred with any of the following names: Peltier device, Peltier heat pump, solid state refrigerator, or thermoelectric cooler (TEC).

Presently, vapour compressor technology is considered a conventional method of cooling because it is fully developed while thermoelectric technology is non-conventional as it is still being developed. In their reports as presented in Wang and Qi (2010), Alhazmy (2006) as well as Bansal and Martin (2000) it was expressed that though vapour-compressor technology is fully developed, they still have many problems to be solved, such as high noise level, strong compressor vibration, and excessive weight and so on. In addition, Riffat and Qiu (2004) stated that the more important problem with vapour-compressor technology is the extensive use of Chlorofluorocarbons (CFCs) or Hydro chlorofluorocarbons (HCFCs), which has a great negative impact on the present crisis of energy and environment.

Due to the advantages observed, Non-conventional cooling systems is finding wide range of applications to meet the energy requirements of the present and future. Some of the advantages of thermoelectric (TE) devices presented in Amandeep et al (2014) by Karimi et al (2011), Yu and Wang (2009), Chen et al (2012), Liu and Wen (2011) are as follows:

- The energy conversion by thermoelectricity is reliable.
- As there are no moving or mechanical parts there is practically no noise or vibration in the setup.
- The portability of a TE chiller would be more as it is relatively smaller in size and lesser in weight as compared to other refrigeration apparatuses such as vapour compression apparatus.

DOI:10.15662/IJAREEIE.2016.0507065

- They pose no threat to the environment as no refrigerant gas such as CFC etc. is used during the refrigeration. Because of the absence of any refrigerant gas the problem of replenishment also does not arise.
- The operational life of a Thermoelectric (TE) module is around 100,000 h of steady state operation.
- The TE device can be used both for cooling as well as heating. By changing the polarity of the DC power supply the heating cycle can be reversed and the heat is pumped in the other direction.
- The TE refrigeration is also a precise technology as it can maintain a temperature control to 0.1°C.
- Thermoelectric (TE) devices are not position-dependent.

Just as it has always been said that everything that has advantage has its own disadvantage too, Thermoelectric (TE) device is not an exception. Amandeep et al (2014) reported that it has lesser efficiency as compared to the vapour compression system i.e. its Coefficient of Performance (COP) is lower than as compared to other mechanical cooling devices. In addition, COP of TE devices gets lower in wide temperature range applications (Gao and Rowe, 2006; Atik and Yildiz, 2012; Yu and Wang, 2009). Amandeep et al (2014) goes further to highlight that one of the approaches being taken to improve the COP of TE modules is researching to develop new materials.

The aim of this work is to investigate the thermoelectric properties of reverse biased silicon Schottky and PN junction diodes in a bid to review a heat absorption model recently presented by Brostow et al (2014). This will enhance modelling silicon as a good refrigerant for efficient industrial and domestic cooling applications.

II. REVIEW OF BROSTOW's POSTULATE

Over the past years, much effort has been put in TE materials research and progress has been made. However researchers like Brostow et al (2014) are of the opinion that significant increase in the performance of TE device can be achieved by improving the module design and fabrication; not just material development with same series arrangement of the P-type and N-type semiconductor materials. In their publication, Brostow et al (2014) expressed the possibility of silicon schottky diodes being good thermoelectric devices.

In forward bias situation displayed as displayed in Fig. 1, Brostow et al (2014) modelled the heat energy released to be:

$$Q_{rel} \equiv \left[E_c - q(V_o - V) + {}^{3k_bT}/_{2} - E_{Fm}\right]({}^{I_F}/_{q}) \qquad (1)$$

And in reverse biased condition as illustrated in Fig. 2, they modelled the rate of energy absorbed to be:

$$Q_{abs} \equiv \left[E_c - q(V_o + V) + {}^{3k_bT}/_{2} - E_{Fm}\right]({}^{I_R}/_{q}) \qquad (2)$$

And for each case, Peltier coefficient is given by:

$$\Pi_F = \frac{Q_{rel}}{I_F} \equiv \left[E_c - q(V_o - V) + {}^{3k_bT}/_{2} - E_{Fm}\right]({}^{1}/_{q}) \qquad (3)$$

$$\Pi_R = \frac{Q_{abs}}{I_R} \equiv \left[E_c - q(V_o + V) + {}^{3k_bT}/_{2} - E_{Fm}\right]({}^{1}/_{q}) \qquad (4)$$

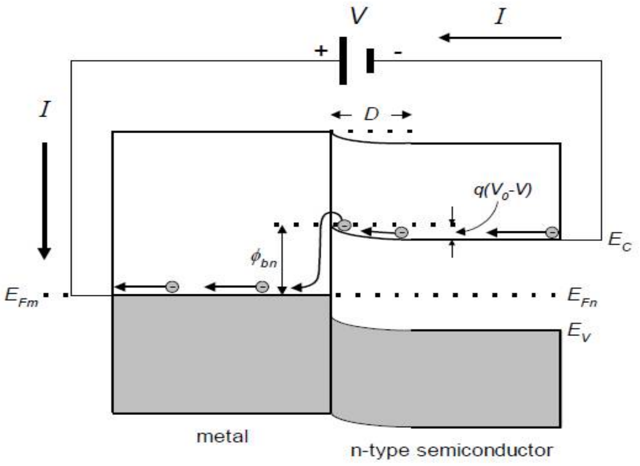

Fig. 1: Forward biased Schottky junction for a metal and n-type semiconductor; heat is released, (Brostow et al, 2014)

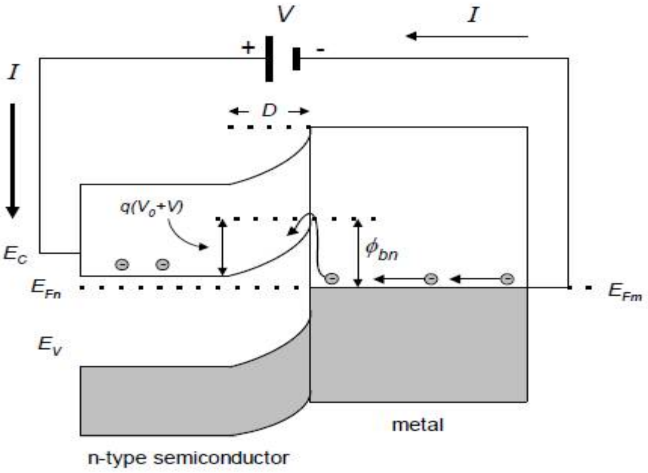

Fig. 2: Reverse biased Schottky junction for metal and n-type semiconductor; heat would be absorbed if there were electron flow, (Brostow et al, 2014)

Equations (3) reveals that the forward bias Schottky junction will exhibit less efficient thermo-electric cooling/heating than the ohmic contact junction. However, the reverse bias heat gain will be primarily through carrier-lattice interactions, and the rate is given by equation (2) while corresponding Peltier coefficient will be given by equation (4)

III. METHODOLOGY

Following this publication by Brostow et al (2014), we have moved a step further to test thermoelectric properties of some commercially available schottky diodes from our local market. The experimental setup was such that a specified number of each diode sample tested was arranged in parallel and connected in reverse bias mode as illustrated in Fig.3; the experimental circuit diagram.

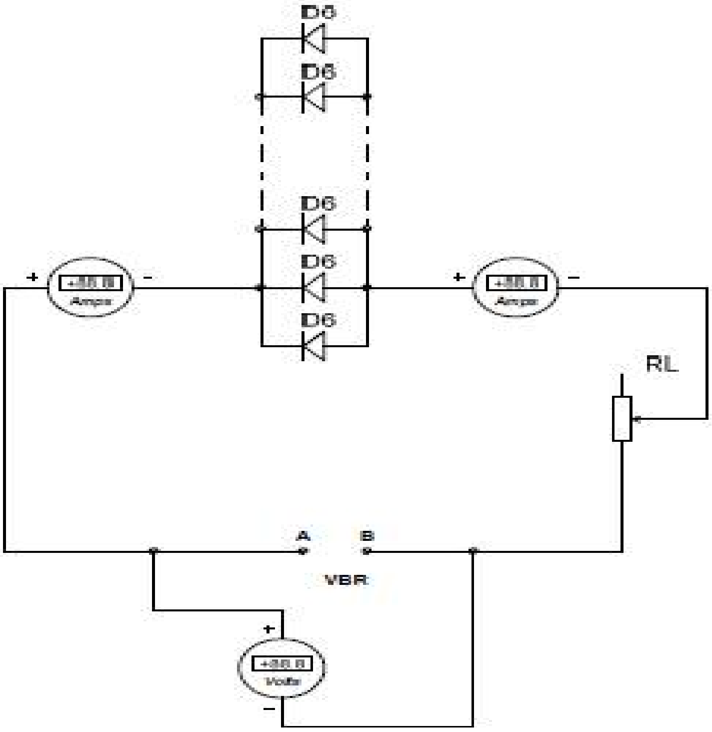

Fig. 3: Experimental circuit diagram

The diodes were placed in a thermally isolated environment in order to monitor temperature change within the environment as would be caused by the diodes, when various level of DC voltages are applied. The thermal enclosure used here is a box whose wall is a composite of wood and Styrofoam, both having a one inch thickness. The interior dimension of this thermal enclosure is $L^3 \cong 0.127^3 m^3$. The wood forms the external part of the box while Styrofoam forms the internal walls.

The interior temperature of the box was monitored using LM35 integrated circuit and a digital multi-meter (ALDA: DT-830D) connected as illustrated in Fig. 4, while the temperature of the external environment was monitored directly with a multi-meter (MASTECH: MS2101).

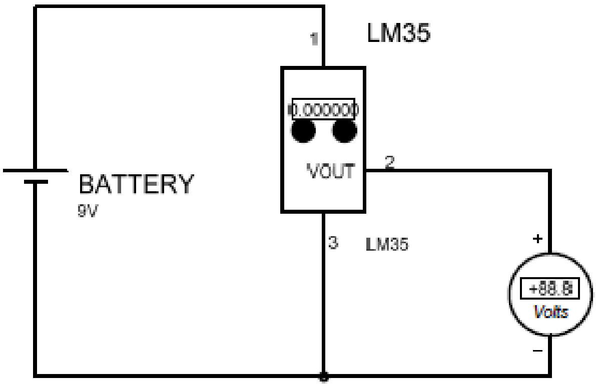

Fig. 4: Temperature Monitoring Circuit

The changes in temperature indicated by both meters with respect to time and applied DC voltage were recorded.
The DC voltage applied to reverse bias the diodes are supplied by an unregulated DC supply unit, whose circuit diagram is expressed in Fig.5. Here, AC source is fed directly to a full bridge rectifier constructed with 1N4007 diodes through a variable transformer (variac). The variable transformer takes input of 240V AC and gives output according to tap changer position ranging from 0 to about 117% of input voltage. The variac is varied while monitoring the voltmeter across points A and B until a desired DC voltage value is reached.

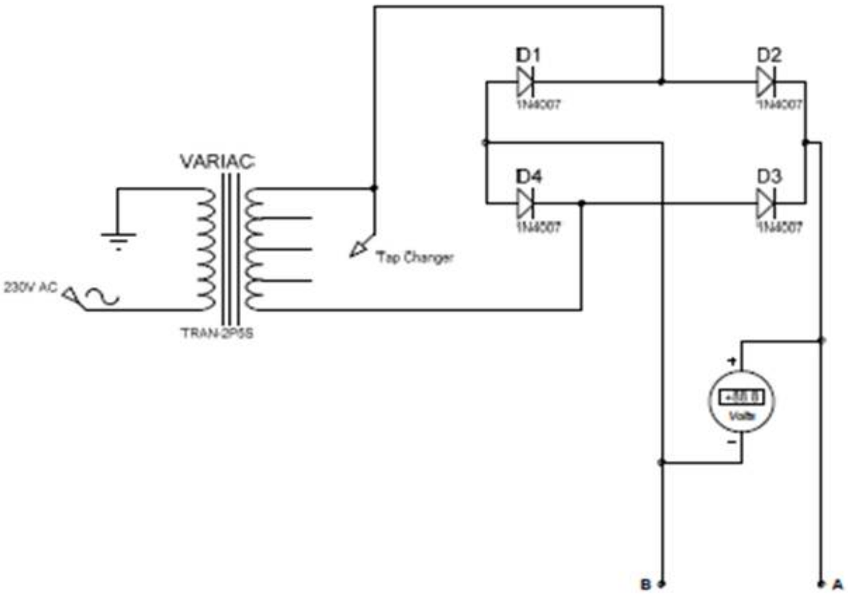

Fig.5: DC supply unit

IV. RESULT AND DISCUSSION

In the course of this work the following diode samples were tested in the lab: 1N5817, 1N5822, 1N5392 and 1N5408. Table 1 shows the diode samples and some of their properties extracted from VISHAY device data sheet for the various sample diodes.

Table 1: Propertied of Tested Diodes

Diode Name	Type	Peak V_{BR} (V)	Peak $I_R$at 25˚C (mA)	Built in Potential, V_o (V)	Average mass (g)
1N5817	Schottky Si diode	20	0.5	0.450	0.332
1N5822	Schottky Si diode	40	2	0.525	1.08
1N5392	General purpose Si diode	100	0.005	1.4	0.336
1N5408	General purpose Si diode	1000	0.005	1.2	1.1

THEORETICAL VALUE OF ABSORBED ENERGY

Upon evaluation of equation (2); the heat absorption rate (Q_{abs}) model of a schottky diode in reverse biased mode as presented by Brostow et al (2014) yields

$$Q_{abs} = [0.8 - 1.6 \times 10^{-19}(V_o + V) + 2.1 \times 10^{-19}T]6.24 \times 10^{18} I_R \qquad (5)$$

Where:

$The\ barrier\ height\ schotkky\ junction, \emptyset_B = E_c - E_{Fm} = 0.8V$

$k_b = Boltzman\ constant = 1.3806 \times 10^{-23} J/K$

$q = 1.6021 \times 10^{-23}\ coloumbs$

$I_R = Peak\ reverse\ current\ (mA)$

$V_o = the\ built\ in\ potential\ for\ schotkky\ junctions$

$V = V_{BR}\ ; applied\ reverse\ bias\ voltage$

$T = Temperature\ (^{\circ}C\ or\ K)$

At Nigerian ambient environmental temperature (30 ˚C = 303K), equation (5) reduces to equation (6) irrespective of built in potential $V_o$magnitude of the device and applied reverse biased voltage, V_{BR}. This condition remains true provided that the magnitude of V_o , V_{BR} and T does not exceed unit of thousand. Hence we have:

$$Q_{abs} = [0.8]6.24 \times 10^{18} I_R \qquad (6)$$

Substituting the values of I_R as expressed in table 1 into equation (6) will yield the following magnitude of heat absorption rate (Q_{abs}), as listed in table 2:

Table 2: The Theoretical Heat Absorption Rate Magnitude

Diode Name	Peak V_{BR} (V)	Peak $I_R$at 25˚C (mA)	Built in Potential, V_o (V)	Average mass (g)	Q_{abs} (Joules)
1N5817	20	0.5	0.450	0.332	2.496×10^{15}
1N5822	40	2	0.525	1.08	9.984×10^{15}
1N5392	100	0.005	1.4	0.336	2.496×10^{13}
1N5408	1000	0.005	1.2	1.1	2.496×10^{13}

The expected rate of change in temperature for each of these tested devices is given by:

$$\Delta T = \frac{Q_{abs}}{c \times m} \qquad (7)$$

Where: m is the average mass of the diodes as specified in Tables 1 and 2 and $c\ is\ the\ specific\ heat\ capacity\ of\ silicon = 0.712\ Jg^{-1}{^{\circ}C}^{-1}$as reported by Dmitry Sinelov (2007).

Hence expected rate of temperature change is presented in table 3 as follows:

Table 3: Expected rate of temperature change

Diode Name	Peak V_{BR} (V)	Peak $I_R$at 25˚C (mA)	Average mass (g)	Q_{abs} (Joules)	ΔT (˚C)
1N5817	20	0.5	0.332	2.496×10^{15}	10.56×10^{13}
1N5822	40	2	1.08	9.984×10^{15}	12.98×10^{13}
1N5392	100	0.005	0.336	2.496×10^{13}	10.43×10^{13}
1N5408	1000	0.005	1.1	2.496×10^{13}	3.19×10^{13}

PRACTICAL VALUE OF HEAT ABSORPTION RATE

The laboratory test on the sample diodes samples 1N5817, 1N5822, 1N5392 and 1N5408 yielded a contradicting result. Both the schottky junctions (1N5817 and 1N5822) and PN junctions (1N5392 and 1N5408) failed to absorb heat in reverse biased mode, irrespective of the applied voltage. Rather they release heat upon breaking down. At voltages below reverse break down voltage, PN junctions appear not to absorb or release heat energy.

1N5817 TEST

Fig. 4 is an illustration of 1N5817 test conditions and results. In reverse bias mode, 1N5817 diode totally blocks current flow at voltages below its breakdown voltage (20V) and does not show any significant rate in temperature change. At voltage equal to or slightly greater than the breakdown voltage, the diode leakage current is of the order of 0.1A and the diode releases heat instead of absorption at a rate of 0.0127 ˚C/min. Once the biasing voltage is made equal to zero (VBR = 0V), the diode immediately absorbs the generated heat from its environment to maintain dynamic equilibrium around its junction by balancing major and minor carrier concentration. Consequently the diode achieves and maintain the environmental temperature of its surroundings.

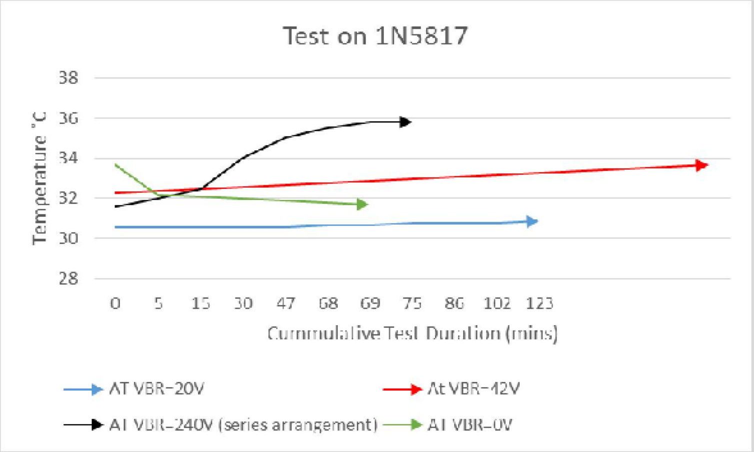

Figure 4: Heat Absorption Characteristics of 1N5817at VBR = 20Vpackets

If a number of 1N5817 is arranged in series the breakdown voltage becomes a resultant of summation of the individual breakdown voltages. On reverse biasing ten pieces of 1N5817 diode in series for thermoelectric property test, the diodes showed no temperature change and no current flow until the reverse bias voltage magnitude reaches 240V. At this condition, the diode sample exhibited a sharp rate of temperature change (0.2 ˚C/min) compared with other test configurations of same device.

TEST ON 1N5822

Upon applying biasing voltage, 1N5822 yielded similar behaviour as 1N5817. Below its breakdown voltage, 1N5822 did not show any sign of heat absorption, rather it releases heat at a very small rate in the order of 0.0056 ˚C/min. At peak reverse biasing voltage (40V), 1N5822 still releases heat instead of absorption. But this time, the heat releasing rate is higher; of the order of 0.0156 ˚C/min. Application of 60V being 150% of the peak break down voltage increased rate of change in temperature to 0.0359 ˚C/min.

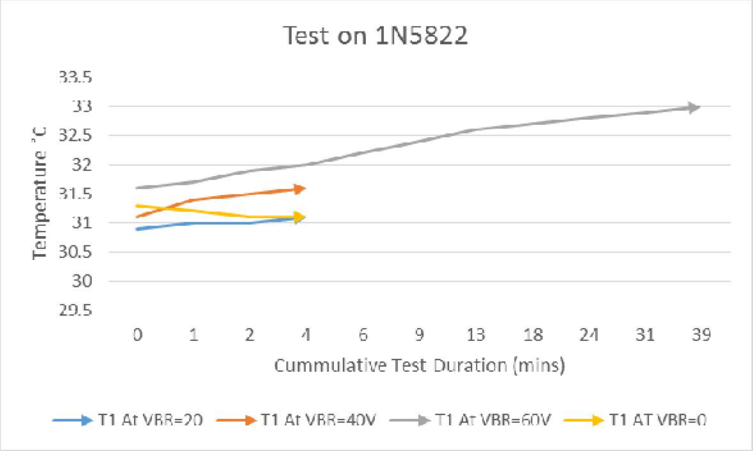

Figure 5: Heat Absorption Characteristics of 1N5822

1N5392 and 1N5408 TESTS

These two diode samples are not schottky junctions, they are silicon PN junctions. At all applied voltage 1N5392 did not show any temperature change. Both the starting and ending temperatures appears to be same. Figure 6 illustrates this.

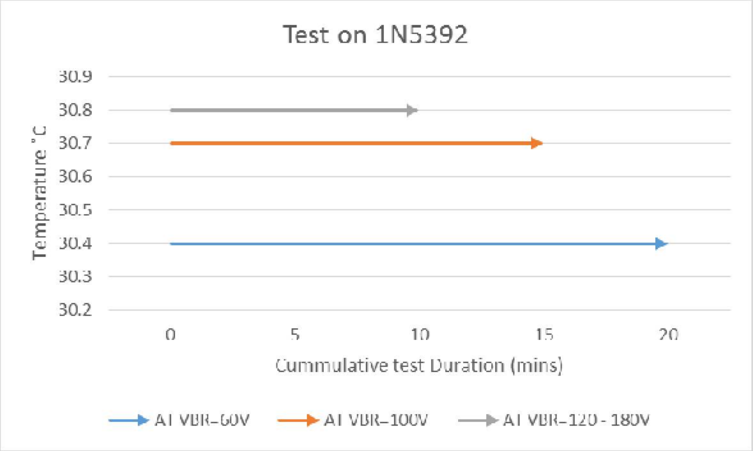

Figure 6: Heat Absorption Characteristics of 1N5392

Due to the capacity of laboratory facilities, the peak breakdown voltage of 1N5408 could not be reached. At the maximum applied reverse voltage during 1N5408 test was 280V. Starting from least voltage applied (50V) to the maximum applied voltage (280V), this diode did not show any temperature change.

V. CONCLUSION AND RECOMMENDATION

The disparity between theoretical heat absorption rate and practical absorption rate is too wide. Yes, this study has confirmed that theoretically, silicon schottky junctions should have a very high heat absorption rate thus confirming Brostow et al (2014) postulates. However, Laboratory test shows that the silicon Schottky junctions and other silicon PN junctions does not absorb heat when they are just reverse biased, rather they release heat. The reason for this huge disparity is not yet very clear, but may be attributed to carrier mobility and carrier concentrations. The sample materials all have high carrier concentrations and consequently high carrier mobility too.

Though, this investigation show that approaching improvement of thermoelectric devices coefficient of performance (COP) through material chemistry research can be more fruitful, it is recommended that further work to be done on reconfiguring the basic PN junction units that are commercially available from series to parallel to see if there would be a better coefficient of performance compared with the status quo.

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