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Performance of shunt voltage regulators based on Zener diodes at cryogenic temperatures

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ABSTRACT

Electronic circuits in certain space missions are exposed to very low temperatures. Very limited data exist on the performance and reliability of electronic devices and circuits at cryogenic temperatures below the manufacturer's specified operating temperature range. This database can be used as a design tool for screening and identifying diodes with potential use in extreme temperature applications. Therefore, the present paper summarizes the preliminary results obtained on the evaluation of shunt voltage regulators based on different breakdowns of Zener diodes whenever they operate at very low temperature levels. The performance of Zener voltage regulator was evaluated under a wide temperature range from 300 to 93 K. In this concern, six sets of Zener diodes of the types BZV86-1V4, BZX83-C3V6, BZX79-C4V7, BZX79-C5V6, BZX83-C6V8 and BZX55C9V1 covering a wide range of low breakdown voltages (from 1.40 to 9.10 V), were chosen. The devices were evaluated in terms of their output voltages at different input voltage levels (line regulation), and at constant load current as a function of temperature. The effect of temperature on load regulation was also established for different load levels up to 21.0 mA, at constant input voltage, over the low temperature range of 300 to 93 K.

Keywords: Low temperatures, Zener diodes, tunnel effect, avalanche effect, shunt voltage regulators.

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INTRODUCTION

As space exploration, satellite communications, and other extraterrestrial activities become increasingly common, the need for electronics that function at extremely low temperatures is a must. The operational temperature of space assets can vary anywhere from a few Kelvin, in the cold of deep space, all the way up to 100 to 200 K for satellites in near earth orbit exposed to the extremes of solar radiation (Ward et al., 2002). While electronics do exist that operate at these temperatures, their development is severely limited by inefficient design tools and prohibitive costs. Two main reasons exist for these limitations; first, there is a lack of simulation and modeling capabilities in the low temperature electronics community. The second reason is due to a perceived need for exotic technologies such as silicon germanium based devices (Cressler, 2005; Allnutt, 2007). So, the present paper will provide a brief background in one type of semiconductor devices, namely: Zener diode, and discuss the low temperature phenomena that affect device performance, as well their applications as shunt voltage regulators. Avalanche diodes (or Zener diodes) are widely employed for voltage regulation or parallel protection against electrostatic discharge or lightening. Two mechanisms of breakdown are present in this kind of diode: avalanche breakdown and Zener (tunneling) breakdown (Nguyen and Paques, 2011).

Voltage regulators based on Zener diodes

Designing of the Zener diode regulator requires the designer to know the minimum and maximum input voltages that are to be regulated, and the minimum and maximum load currents. The Zener diode must handle

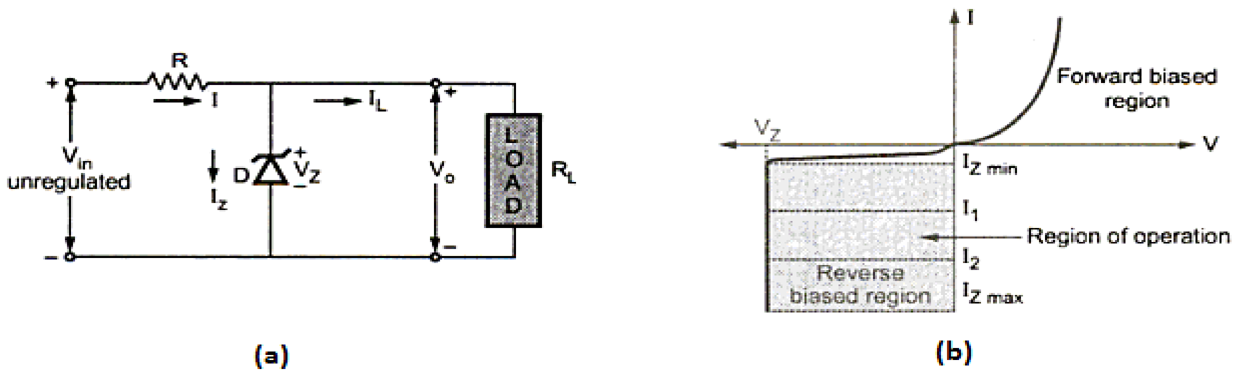

Figure 1. (a) Zener diode as shunt regulator; (b) V-I characteristics of Zener diode.

any current that would normally pass through the load when it changes and the demand for current decreases. Figure 1a shows a typical circuit of the Zener diode circuit design (Akturk et al., 2006). To understand the working of the circuit, one must revise the V-I characteristics of a Zener diode (Figure 1b).

Voltage regulator performance parameters

Output resistance (R_o)

The change in the load voltage V_o due to the change in the load current I_L is expressed in terms of a ratio, which gives the output resistance of a regulator, denoted as R_o:

$$R_o = \left.\frac{\Delta V_o}{\Delta I_L}\right|_{\text{constant } V_{in}, T} \qquad (1)$$

where, ΔV_o is the change in load voltage, and ΔI_L is the change in load current.

While defining this parameter, the other two factors V_{in} and temperature T are assumed constant. Ideal value of R_o is zero. Under such condition, the voltage regulator behaves as a constant voltage source or battery.

Voltage stability factor (S_V)

The change in the load voltage due to the change in input voltage (line voltage) is expressed in terms of a factor called line regulation or the voltage stabilization factor S_V, where:

$$S_v = \left.\frac{\Delta V_o}{\Delta V_{in}}\right|_{\text{constant } I_L, T} \qquad (2)$$

where, ΔV_o and ΔV_{in} are the changes in the load–and line–voltages. The ideal value of S_v is zero.

Temperature stability factor (S_T)

The change in the load voltage due to the change in the temperature is expressed by a factor called the temperature stability factor S_T or the temperature coefficient of the output voltage, which is given as:

$$S_T = \left.\frac{\Delta V_o}{\Delta T}\right|_{\text{constant } I_L, V_{in}} \qquad (3)$$

where, ΔV_o and ΔT are the changes in both the load voltage and temperature, respectively. The ideal value of S_T is zero (Godse and Bakshi, 2009).

MATERIALS AND METHODS

Different breakdown silicon Zener diodes were chosen for studying their electrical properties whenever they operate at very low temperature levels, down to cryogenic levels, simulating their application at outer space environment. In this concern, six different Zener diode sets covering the breakdown voltage range from 1.40 to 9.10 V were chosen during the course of the study. Performance characterization was obtained in term reverse voltage-current characteristics applying curve tracer of the type Tektronix 370A curve tracer. All measurements were carried out at different temperature levels within the range from room level (293 K) down to cryogenic level (93 K) using the set up shown in Figure 2 (El-Ghanam and Basit, 2011). A temperature rate of change of 10°C /min was used, and a soak time of at least 20 min was allowed at every test temperature.

The paper was extended to include the applications of the devices as a shunt regulator (Figure 1a), where the peak input resistor (R) is 470 Ω and load resistor (R_L) is 3.30 kΩ. The voltage regulator device was evaluated at the test temperatures of 93, 150, 227 and 300 K in a liquid nitrogen cooled environmental chamber.

RESULTS AND DISCUSSION

Low temperature dependence of reverse V-I characteristics

As the temperature decreases, there are two physical

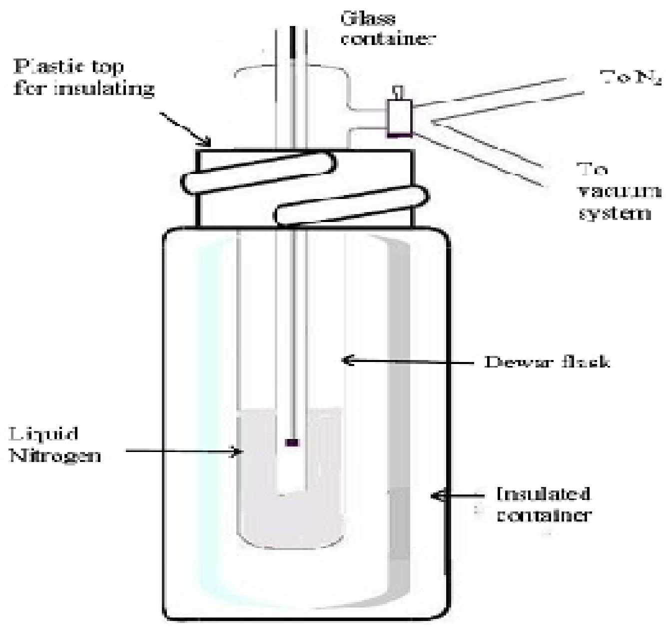

Figure 2. Cooling system used for controlling the samples low temperature levels.

phenomena that dominate device operation, increased mobility and incomplete ionization. High mobility is generally good for component performance as long as it can be modeled. Mobility is determined by two main scattering mechanisms, electron-phonon scattering and impurity scattering. Electron-phonon scattering is due to scattering in the silicon lattice, while impurity scattering is due to ionized impurities. At higher temperatures (near room temperature), scattering by ionized impurities is less effective since the faster moving carriers interact less effectively with stationary impurities. Initially, as temperature decreases, mobility increases due to a decrease in the electron-phonon scattering rate (Akturk et al., 2005; Akturk et al., 2005; Gaensslen et al., 1977; Szmyrka-Grtebyk and Lipiriski, 1995). Temperature variations can have a significant effect on the electrical characteristics of a semiconductor diodes, the matter which is clearly shown in Figure 3, for the case of the proposed Zener diodes of types: BZV86-1V4, BZX83-C3V6, BZX79-C4V7, BZX79-C5V6, BZX83-C6V8 and BZX55C9V1. There are two breakdown mechanisms of diode due to concentration of impurities by increasing the reverse voltage across it, that is, Zener breakdown and avalanche multiplication. In this concern, the experimental reverse (V-I) characteristics of the proposed six Zener diodes are shown in Figure 3, including breakdown regions. It is clearly shown, in Figure 3, that the Zener voltage is a modest function of temperature. An accurate low temperature model, however, must also include the effects of impurity concentration as it pertains to incomplete ionization (Fang and Fowler, 1965; Akturk et al., 2006). The coefficient is negative for a diode with a reference voltage below about 5.0 V (Figure 3a and b); otherwise it is positive, as shown in Figure 3c, d, e and f. This is related to the dominance of one or the other of the two phenomena producing similar terminal breakdown characteristics.

Low temperature dependence Zener voltage regulator

Line regulation

Voltage regulation is the process of taking the unregulated input voltage and producing a constant output voltage under varying input voltage (Stout et al., 2008). Line regulation characteristics based on the proposed different Zener diodes were obtained over the test temperature levels of 93, 150, 227 and 300 K. The dependence of the voltage regulator output on its input voltage at constant load current is depicted in Figure 4, plotted at the selected test temperatures. From which, it is clearly shown that, for the reverse bias region (Figure 3), at low input signals (V_{in}), the Zener diode is in reverse-bias, but not yet in breakdown region. So, the Zener diode acts as an open-circuit and has negligible effect on circuit operation. As a result, the diodes do not conduct current, as the input voltage is less than the Zener voltage. In this case, R and R_L in circuit of Figure 1a form a resistive voltage divider, making output voltage (V_{out}) somewhat smaller than input voltage (V_{in}), and so the regulation curve is a line segment (Godse and Bakshi, 2008).

On the other hand, as the input voltage increases up to a value more than that of V_Z (2.0, 5.0, 5.0, 6.0, 8.0 and 10.0 V) for the proposed Zener diodes, respectively, the Zener diodes conduct (Figure 4). With a further increase in V_{in}, the input current (I) will also increase. This increases the current through the Zener diode (I_Z) without affecting the load current (I_L). The regulated output voltage of the regulator exhibited negative temperature coefficient for the Zener diode of types: BZV86-1V4 and BZX83-C3V6, while for Zener diode of types BZX83-C6V8 and BZX55C9V1, its value has positive temperature coefficient. The test temperatures have had little effects on the ability of the regulator to maintain good line regulation for the Zener diodes of types BZX79-C4V7 and BZX79-C5V6.

Characterization of line regulation:

Zener regulation voltage and temperature stability factor (S_T):

The dependence of the Zener regulation voltage on temperature for the proposed diodes was shown in

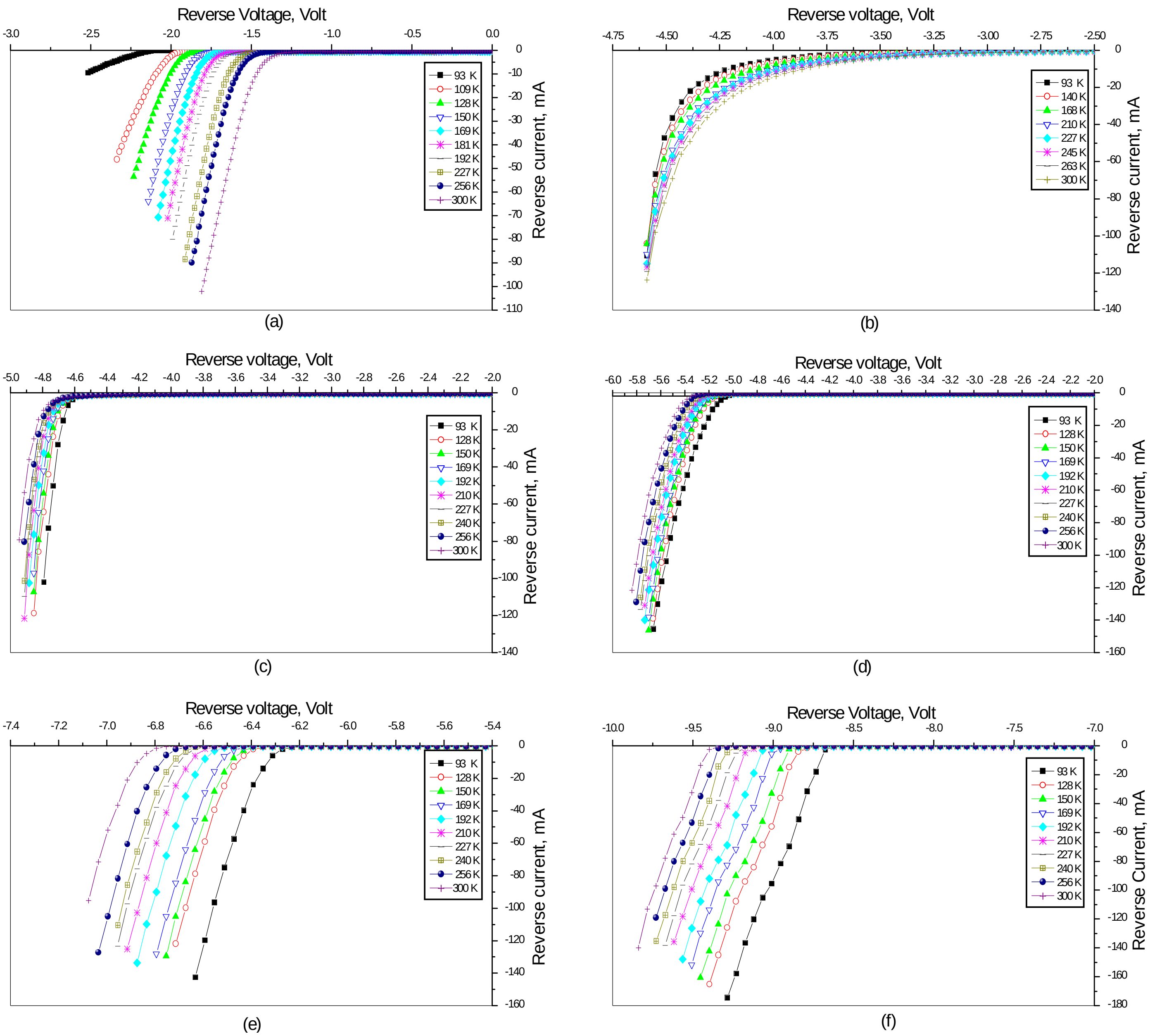

Figure 3. Reverse (I-V) characteristic curves of the proposed Zener diodes; (a) BZV86-1V4, (b) BZX83-C3V6, (c) BZX79-C4V7, (d) BZX79-C5V6, (e) BZX83-C6V8, and (f) BZX55C9V1, plotted at different temperature levels.

Figure 5. On the other hand, the temperature stability factor (S_T) of the devices as a function of the Zener breakdown voltage was plotted as shown in Figure 6. From which, it is clearly shown that for Zener diodes having low breakdown voltages, that is, $V_Z \leq 5.0$ V (BZV86-1V4, and BZX83-C3V6), the temperature coefficients are negative. So, their breakdown voltages were proved to be decreased as a function of temperature level (Figure 5a). The matter is mainly due to their high doping levels, and hence, Zener (tunnel) effect dominates. On the other hand, for Zener diodes with V_Z greater than 6.0 V (BZX83-C6V8 and BZX55C9V1), the temperature coefficient is positive, as shown in Figure 6, so V_Z increases as temperature increases (Figure 5c), where such diodes are characterized with their low doping levels and higher voltages, so the avalanche effect dominates. Finally, at certain doping level and breakdown voltages of approximately 5.0 to 6.0 V (for Zener diodes of the type BZX79-C4V7 and BZX79-C5V6), it was noticed that the avalanche effect and the tunnel effect are both present. Therefore, as the temperature decreases, the breakdown voltage decreases due to the avalanche effect and increases due to the tunnel effect, so that the changes in breakdown

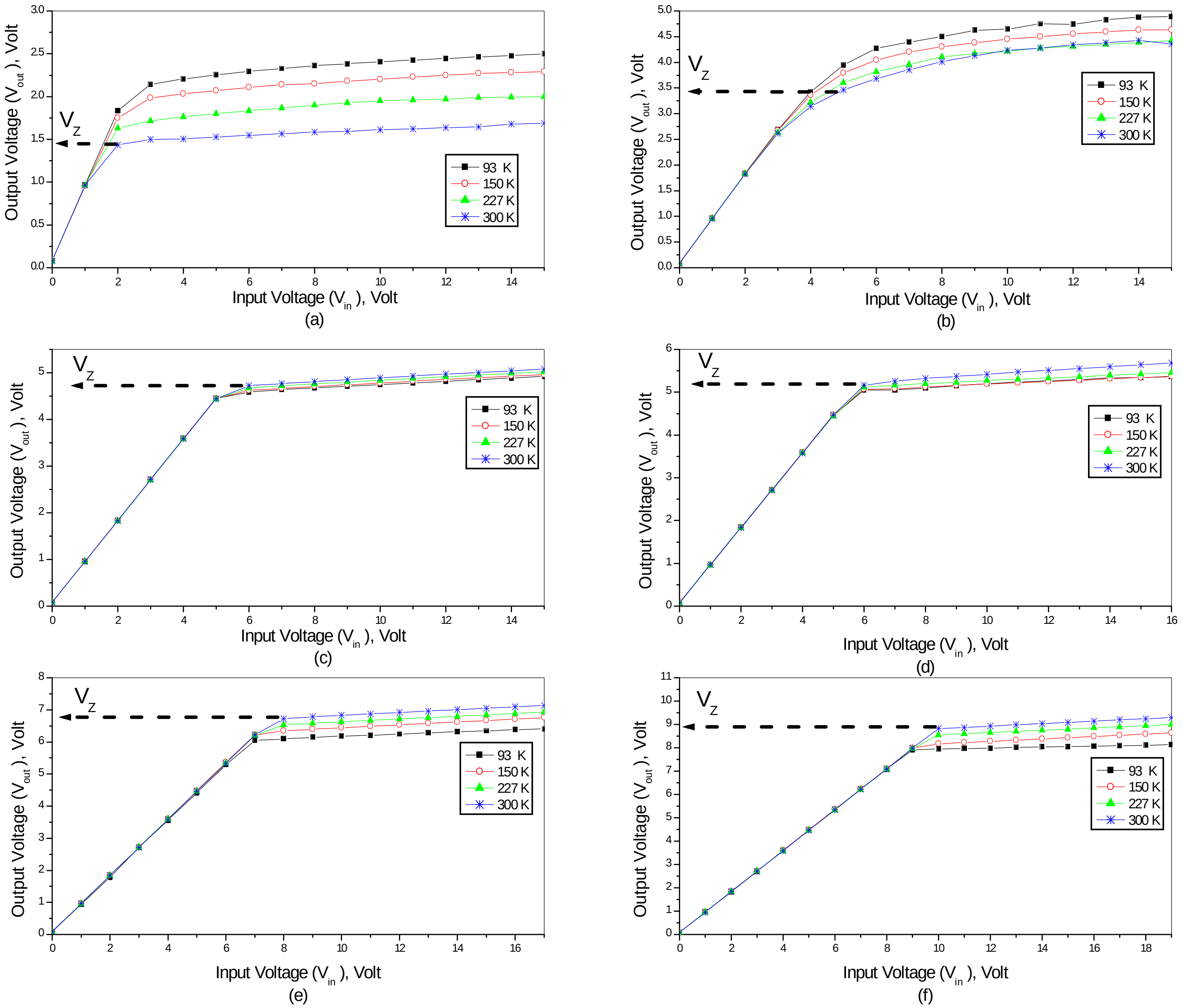

Figure 4. Output voltage versus input voltage for different Zener diodes; (a) BZV86-1V4, (b) BZX83-C3V6, (c) BZX79-C4V7, (d) BZX79-C5V6, (e) BZX83-C6V8, and (f) BZX55C9V1, plotted at four low temperature levels.

voltage due to different phenomena are cancelled by each other (Figure 6). As a result, the temperature coefficient of the breakdown voltage is substantially zero (Kumano, 1996). So, the value of the Zener regulation voltage for Zener breakdown voltages of approximately 5.0 to 6.0 V was proved to be slightly affected by lowering temperature (Figure 5b). The obtained results were shown to be consistent with those obtained for the effects of high temperatures on the diodes, where, when Zener voltage is below 5.0 V, the Zener effect dominates negative temperature coefficient as shown in Figure 6. On the other hand, higher Zener voltage diodes produce the effect at a positive temperature coefficient Vasileva, 2009.

Voltage stability factor (S_v):

The voltage stability factor, which is a measure of percentage change from pre-determined line regulation value, was studied, where it is reported that its value increases from 2.0%, measured at 300 K, up to 5.0%, measured at 93 K, for shunt voltage regulator based on the Zener diode of type BZV86-1V4, as shown in Figure 7. While its value was shown to be reduced from the values of 4.60 and 5.30% down to 3.4%, and 2.20% for BZX83-C6V8 and BZX55C9V1 Zener diodes, for the same range of temperatures. The values of voltage stability factor for the rest of diodes were shown to be

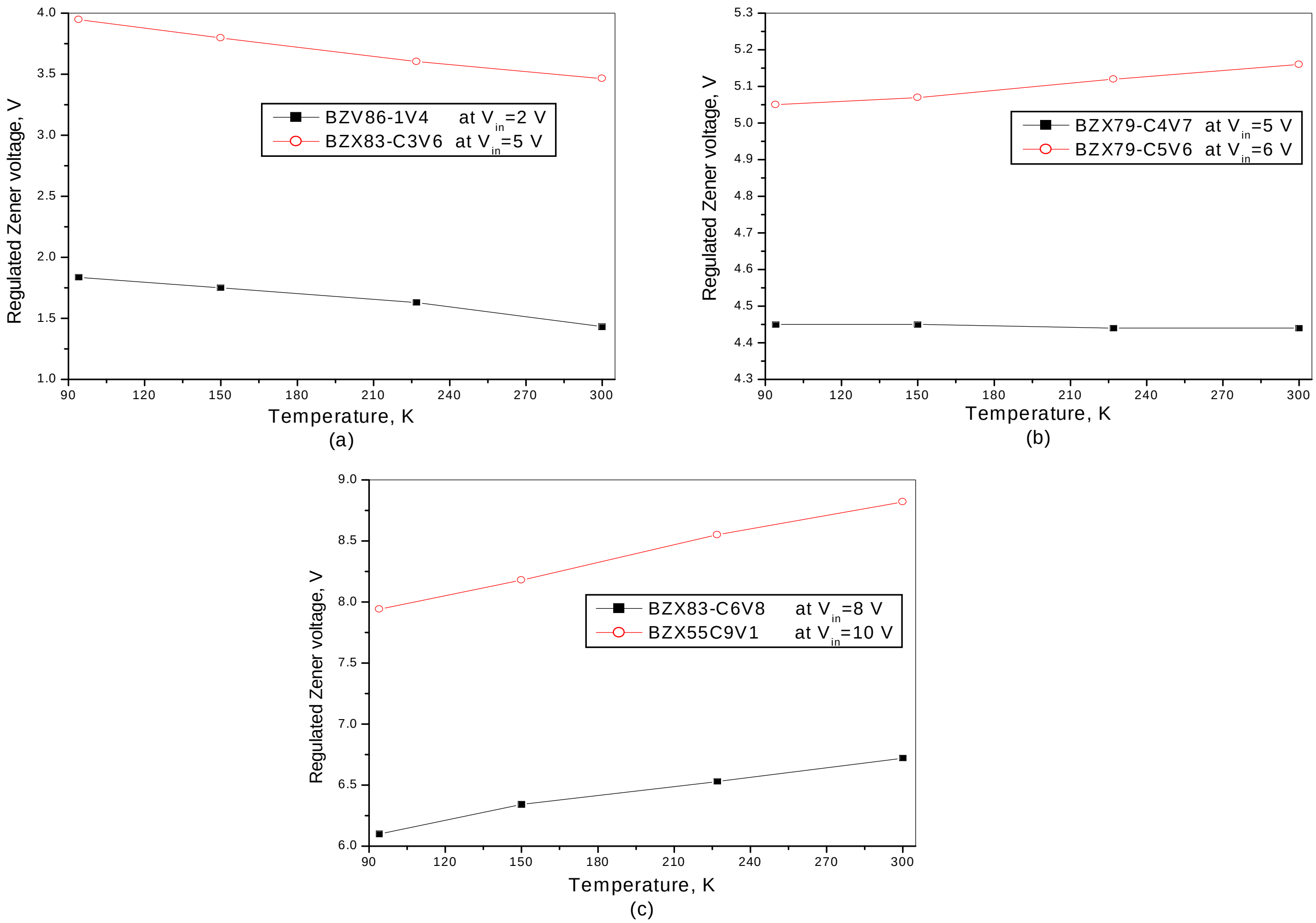

Figure 5. Dependence of Zener regulation voltage on temperature for the proposed diodes.

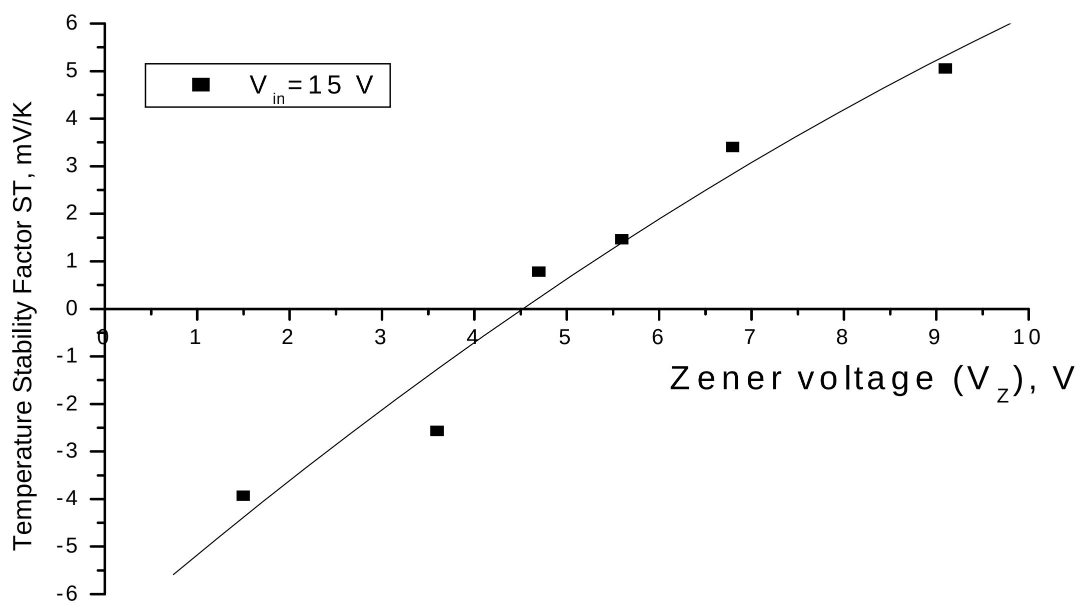

Figure 6. Temperature stability factor (S_T) versus Zener breakdown voltage for the proposed six diodes.

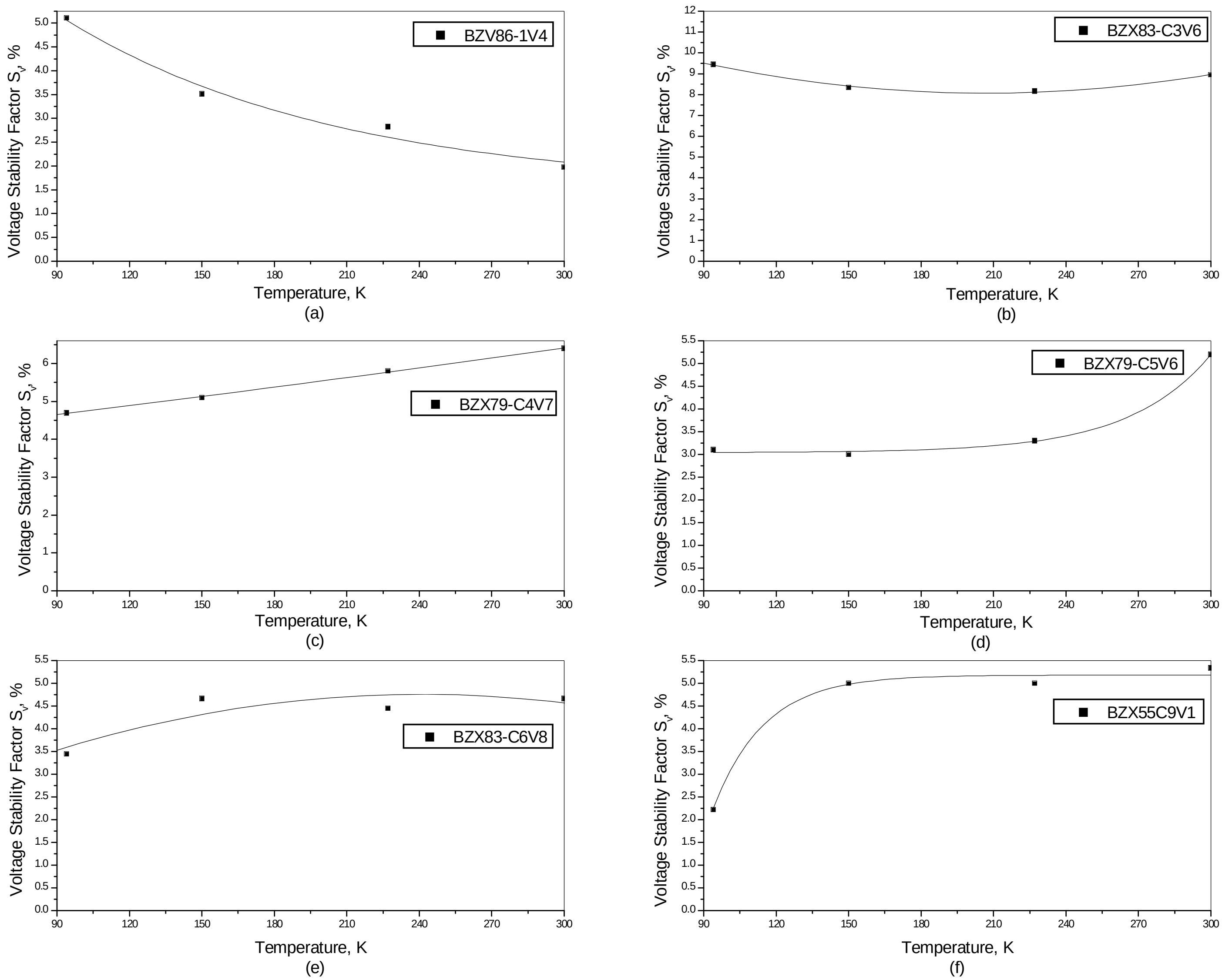

Figure 7. Voltage stability factor (S_v) versus temperature for the proposed Zener diodes.

slightly affected by lowering temperature from 300 to 93 K.

Load regulation

Variations in the output voltage of the proposed Zener diodes as a function of the load current were plotted at four temperature levels (300, 227, 150 and 93 K), as shown in Figure 8. It is clear that the variation of load resistance (R_L) changes the load current (I_L) through it, thereby changing the output voltage. When the load resistance decreases, the current through it increases. This ultimately causes a decrease in the Zener current. As a result, the input current and the voltage drop across R remain constant, and the output voltage is also kept constant. On the other hand, as the load resistance increases, the load current decreases, hence the Zener current increases. This again keeps the value of input current and voltage drop across the series resistance constant. Thus, the output voltage remains constant; this is called load regulation (Godse and Bakshi, 2009). This data was recorded with an applied input voltage of 10 V for Zener diodes of the type BZV86-1V4, BZX83-C3V6, BZX79-C4V7, BZX79-C5V6 and BZX83-C6V8, and 12 V for BZX55C9V1 diodes.

Characterization of load regulation:

Output resistance:

The change in the load voltage (V_{NL}-V_{FL}) divided by the change in load current (I_{FL}) equals the output resistance

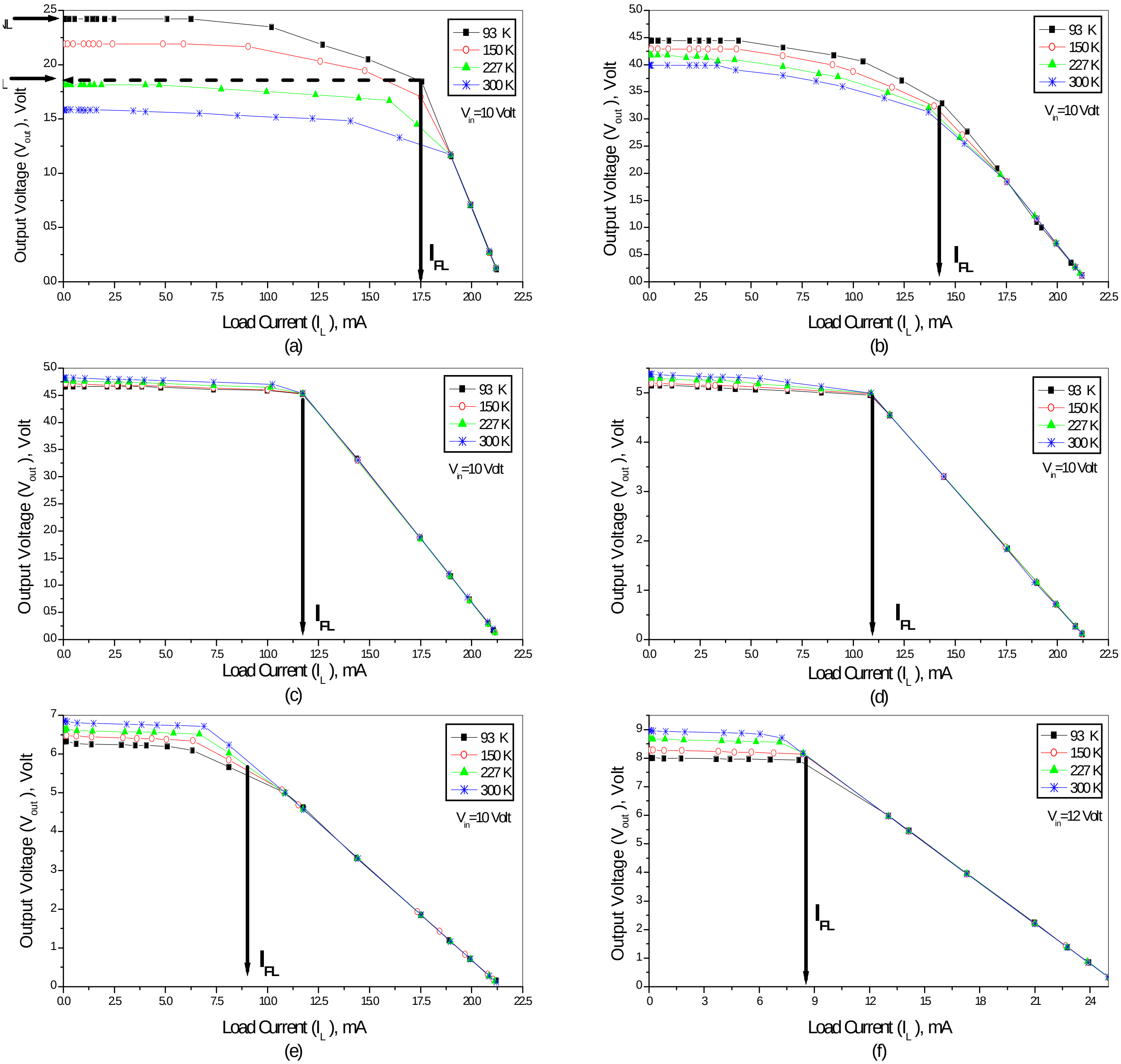

Figure 8. Output voltage versus load current, plotted for the proposed six Zener diodes (a) BZV86-1V4, (b) BZX83-C3V6, (c) BZX79-C4V7, (d) BZX79-C5V6, (e) BZX83-C6V8, and (f) BZX55C9V1.

(R_o) of the regulator (Figure 8), where the output resistance is related to the slope of this graph. The maximum load current (I_{FL}) occurs when the load resistance is minimum (Kachhava, 2003). The trend of the output voltage versus output current (load current) was linear in nature with a characteristic slope (output resistance) ranging between: 18.0 Ω at 300 K, and 33.0 Ω at 93 K for BZV86-1V4, and between 92.0 Ω at 300 K and 2.30 Ω at 93 K for BZX55C9V1, as an example, as displayed in Figure 9.

Percentage of load regulation:

The dependence of the load regulation, in percentage, plotted at different low temperatures levels, was shown in

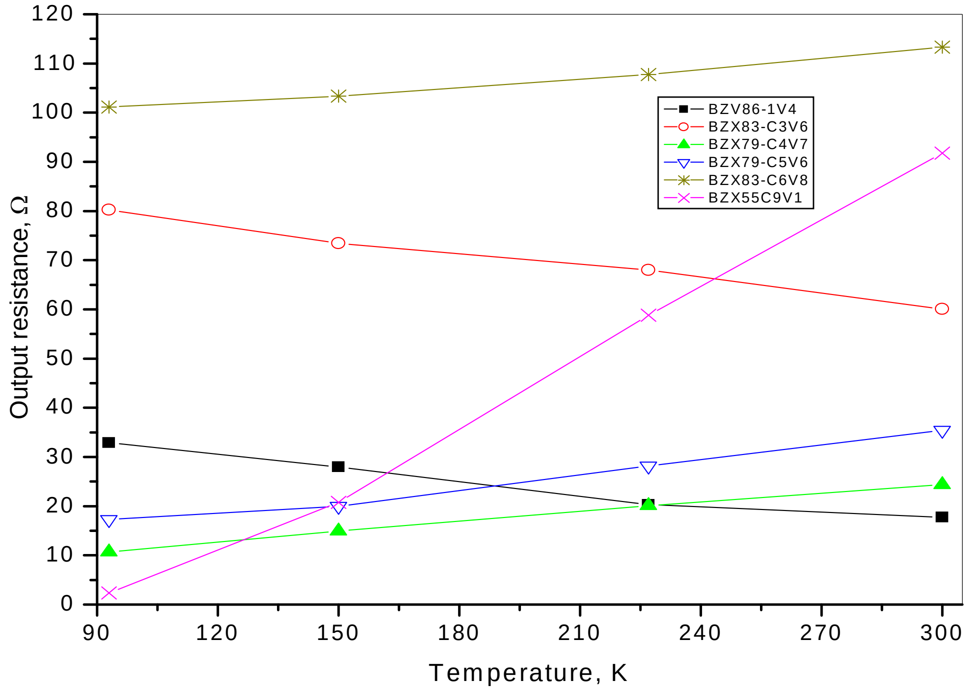

Figure 9. Output resistance of a regulator versus temperature for the proposed six Zener diodes.

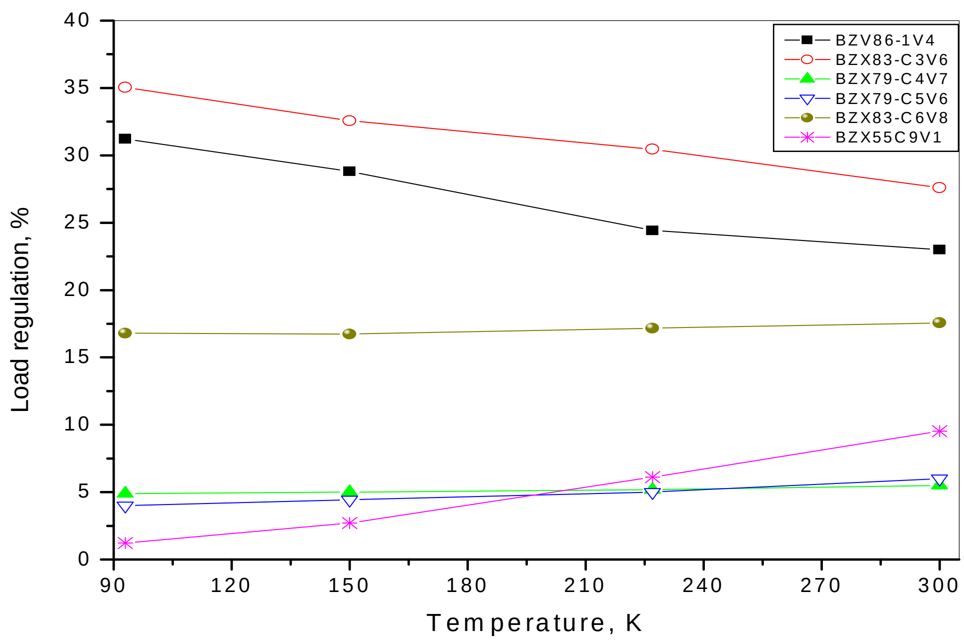

Figure 10. Load regulation percentage versus temperature for the proposed six Zener diodes.

Figure 10. The load regulation is often expressed as percentage using the following equation:

$$\% LR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 \quad (4)$$

From which, it is clear that for the low zener voltage diodes (BZV86-1V4 and BZX83-C3V6), their intial load regulation ratios value of 23.0 and 27.0% were shown to increase up to about 31.0 and 35.0% respecrively, due to lowering temperature from 300 to 93 K. On the other hand, for the 4.70 and 5.6 V zener diodes (BZX79-C4V7 and BZX79-C5V6B), the dependence of their load regulation percentage on temperature, was shown to be approximately negligible, that is its value was shown to decrease from around 17.5 to 16.7%. Finally, for the rest diodes (ZX83-C6V8 and BZX55C9V1) the percentage of load regulation decreases with lowering the temperature levels, that is, from 17.5 and 9.5%, measured at 300 K down to 16.7 and 1.20%, measured at 93 K for the two diodes, respectively.

CONCLUSIONS

The present work is mainly concerned with the design, applications, and studying of the performance of shunt voltage regulator circuits based on Zener diodes on low temperature levels down to 93 K. From the experimental work and analysis of the obtained results, it can be concluded that the effect of low temperature on the reverse I-V characteristic of the investigated diodes, relationship between regulated output-and input-voltages of the investigated diode circuits, voltage stability factor for the investigated diodes, output voltage versus load current for different investigated load and regulated output resistance, were studied. The results show that the investigated parameters of the diodes are direct functions of the temperature level, for Zener breakdown voltages ≤ 5.0 V and ≥ 6.0 V. The dependence of the output of Zener voltage regulator, and the line-and load-regulation characteristics on temperature was traced in the range from 300 to 93 K. From which, the dependence of both the line- and load-regulations of the Zener voltage regulator on temperature within the proposed range was shown to be function of the used Zener diode breakdown voltage. That is, for the low voltage Zener diodes (BZV86-1V4 and BZX83-C3V6), their regulated output voltages were shown to be increased at 93 K. On the other hand, for high breakdown Zener diodes (BZX83-C6V8 and BZX55C9V), an opposite trend was noticed. Finally, the devices with intermediate breakdown voltages (BZX79-C4V7 and BZX79-C5V6) were shown to be very stable against temperature variations.

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