2.3. Temperature-compensated Zener diodes

Attempts were made at an early stage to replace by Zener diodes the standard cells [29] then used as voltage reference sources. These cells were heavy and expensive and of limited usefulness. In 1960, INTERMETALL presented the silicon reference elements BZY 22 . . . 25 [20] which, at best, operated with a temperature coeffizient of the operating voltage $\alpha_{VZ} < 10^{-5}/^{\circ}C$ for a current of 5 mA. The operating voltage amounted to 8.4 V. However, the manufacture of these reference elements was very labour-intensive, so that in 1967 the time was considered ripe for integrated components, i. e. temperature-compensated Zener diodes. At first, INTERMETALL put the ZTK 33 on the market [30] which was developed specifically for stabilising the tuning voltage of diode operated TV tuners [18]. Later developments resulted in a whole series of temperature-compensated Zener diodes, comprising the types ZTK 6,8 . . . ZTK 33.

2.3.1. Methods of temperature compensation

It will be gathered from Fig. 17 that temperature compensation of the operating voltage of Zener diodes, achieved by the series connection of forward-biased silicon diodes makes sense only if the temperature coefficient of the Zener diode is independent of temperature, i. e. if the characteristic of ΔV_Z versus T_j in Fig. 17 is a straight line. This is the case for $V_Z > 6$ V [20]. There are essentially three methods of temperature compensation which are shown diagrammatically in Fig. 36 [11].

Fig. 36a shows a series circuit of discrete semiconductor components such as were used in these reference elements. The operating characteristic of this circuit arrangement differs only little from that of a simple Zener diode, but suffers from the disadvantage of a relatively high inherent differential resistance, since the resistance values of the several diodes are added to each other. The thermal coupling between the diodes, and thus the dynamic component of the temperature compensation is not particularly good.

Improved properties can be achieved with discrete semiconductor components in circuit Fig. 36b which contains a shunt transistor that may also be designed as a Darlington circuit. Due to the current gain of the transistor, a small inherent differential resistance is achieved in this arrangement. Here, too, bad thermal coupling is a disadvantage.

The best method is the integration of the shunt transistor circuit, as outlined in Fig. 36c. Here, the shunt transistor ensures that the inherent differential resistance remains very low, and since the complete circuit can be accomodated on an extremely small 0.5 x 0.5 mm^2 silicon chip, good thermal coupling between all components is ensured. In Fig. 36c, the Zener diode is realised by the emitter diode of a transistor operating under reverse breakdown conditions, with an operating voltage of approximately 6 V.

The operating characteristic of the circuits illustrated in Fig. 36b and c differs in one significant respect from that of a conventional Zener diode

(Fig. 36a). There is no sudden rise in current when the voltage applied to the circuit terminals in Fig. 36c reaches the breakdown level of the emitter diode of the transistor acting as a Zener diode. Instead, it rises according to a characteristic which takes resistor *R* into account. It is only when base current begins to flow in the shunt transistor as a result of the voltage increasing further that the characteristic rises steeply and merges into the actual operating region.

2.3.2. The construction of ZTK diodes

All temperature-compensated monolithic integrated Zener diodes of the series ZTK 6,8 . . . ZTK 33, developed by INTERMETALL, are based on the simple shunt transistor circuit of Fig. 36c. In devices designed for higher output voltages than 7 V, several transistors operating as Zener diodes are connected in series each of which, in theory, has to be temperature-compensated by means of one or two forward-biased diodes connected in series thereto. Instead of such diodes, the ZTK diodes comprise a so-called "adjustment stage" of a kind already described

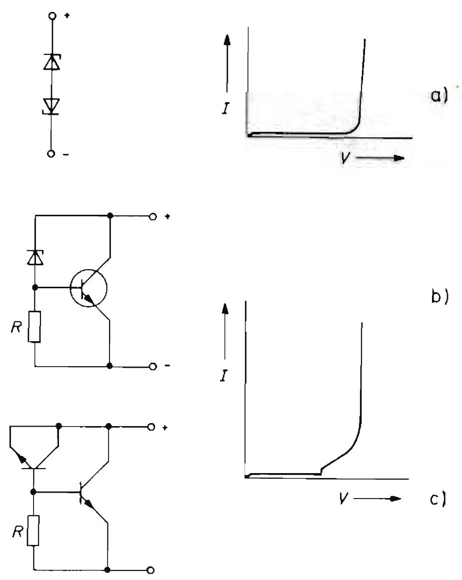

Fig. 36: Methods of temperature compensation
a) Series circuit of several discrete diodes
b) Circuit with Zener diode and shunt transistor, made up of discrete semiconductors
c) Monolithic integrated circuit with Zener diode and shunt transistor

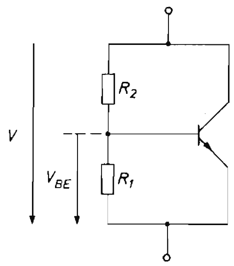

Fig. 37: Adjustment stage

briefly with reference to Fig. 32. Fig. 37 illustrates once more the circuit diagram of such an adjustment stage [27], [28] to which the following expression applies, provided the transistor operates with a sufficiently high current gain.

$$V = V_{BE} \cdot \frac{R_1 + R_2}{R_1} = V_{BE} \cdot \left(1 + \frac{R_2}{R_1}\right) \tag{34}$$

If the base emitter voltage V_{BE} changes as a result of temperature variations, the voltage V also changes, according to the following expression:

$$\frac{dV}{dT} = \frac{R_1 + R_2}{R_1} \cdot \frac{dV_{BE}}{dT}\,; \tag{35}$$

for in a monolithic integrated circuit the ratio of resistors is virtually independent of temperature. With the aid of this adjustment stage, a voltage V is produced which may be any desired – not necessarily integral – multiple of a base emitter voltage V_{BE}, its temperature coefficient being equal to the temperature coefficient of the base emitter voltage of a transistor. This ensures a temperature compensation more accurate than that achievable by means of several diodes in a simple series circuit in which fractions of V_{BE} cannot be realised.

Referring to type ZTK 22, the internal circuit of a ZTK diode (Fig. 38) will now be discussed. Two transistors operating as Zener diodes, each with

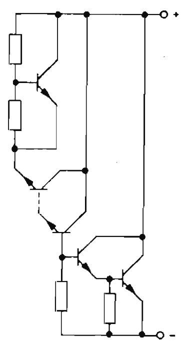

Fig. 38: Internal circuit of the ZTK 22

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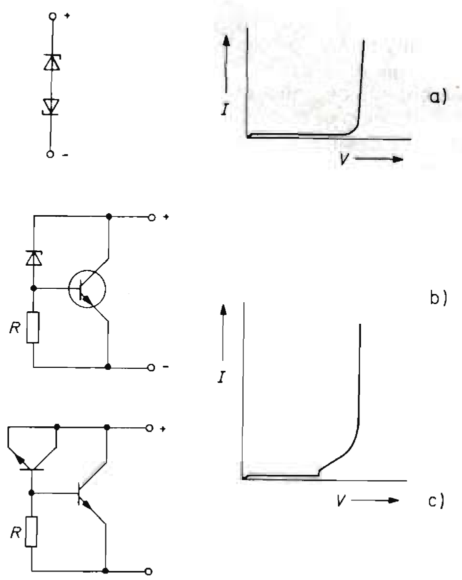

Fig. 36: Methods of temperature compensation
a) Series circuit of several discrete diodes
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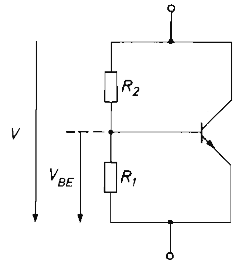
c) Monolithic integrated circuit with Zener diode and shunt transistor



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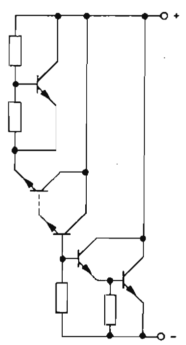
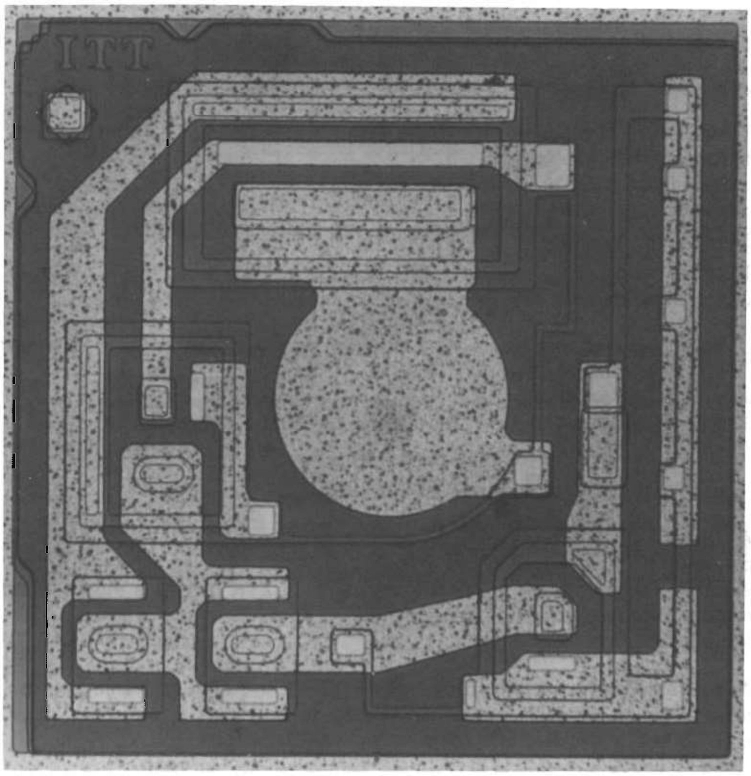


Fig. 38: Internal circuit of the ZTK 22

an emitter to base breakdown voltage of approximately 9 V, are available. To the 18 volts thus obtained must be added a base emitter voltage of the Darlington stage amounting to approximately 1.3 V. This results in 19.3 V, and the residual 2.7 V are taken over by the adjustment stage. For the ZTK 22, a circuit arrangement comprising three transistors acting as Zener diodes would also be feasible, but in this case each of them should have an emitter to base breakdown voltage of 6 V.

The circuit arrangement of Fig. 38 is characterised by a special feature: The collectors of all transistors are at common potential. This does away with the need for electrical separation of the collectors by means of so-called isolation channels. The resulting structure of the ZTK diodes is thus considerably simplified, see Fig. 39. The chip has an area of approximately 0.5 x 0.5 mm^2, so that it can be easily accommodated in a glass case DO-35 (Fig. 11). A special advantage gained with this small glass encapsulation is the extremely short thermal run-in time of only 20 s, this being an important factor when the stabiliser is employed for the tuning voltage of TV tuners.

Fig. 39: The chip of a ZTK diode, magnification approximately 200 times



2.3.3. Data of the ZTK diodes ZTK 6,8 . . . ZTK 33

The table below contains the most important data of the ZTK series.

Table 4:
Main data of the temperature compensated Zener diodes ZTK 6,8 . . . ZTK 33

Type	Operating voltage at $I_Z = 5$ mA	Dynamic resistance at $I_Z = 5$ mA	maximum operating current [1] at $T_{amb} = 45$ °C
	V_Z V	r_{zj} Ω	I_Z mA
ZTK 6,8	6.4 . . . 7.1	10 (< 25)	36
ZTK 9	9 . . . 10	10 (< 25)	27
ZTK 11	10 . . . 12	10 (< 25)	19
ZTK 18	16 . . . 20	11 (< 25)	13
ZTK 22	20 . . . 24	11 (< 25)	10
ZTK 27	24 . . . 30	12 (< 25)	8
ZTK 33 (≈ TAA 550)	30 . . . 36	12 (< 25)	7

admissible junction temperature	T_j	150	°C
admissible storage temp. range	T_S	– 20 . . . +150	°C
Temperature coefficient of the operating voltage at $I_Z = 5$ mA ± 0.5 mA in the range of $T_{amb} = 20 \ldots 60$ °C	α_{VZ}	– 2 (– 10 . . . +5) [1]	10^{-5}/°C
Thermal run-in time	t_{th}	20 [2]	s
Thermal resistance Junction to ambient air	R_{thA}	< 0.4 [1]	°C/mW

[1]) Valid provided that leads are kept at ambient temperature at a distance of 8 mm from the case.

[2]) At the end of this time ΔV_Z has reached 90 % of its final value ΔV_{Zmax}
$\Delta V_{Zmax} = |V_Z(\alpha) - V_Z(0)|$
where V_Z (0) = V_Z in the instant of turn-on
and V_Z (α) = V_Z at thermal equilibrium.

A comparison with the simple Zener diodes of series ZPD, listed in table 2 on page 32, shows that types ZTK 8 . . . ZTK 33 have an inherent differential resistance which is much lower, and all ZTK diodes a much lower temperature coefficient of the operating voltage. This can also be ascertained from Figs. 40 and 41.

A mathematical comparison of types ZPD 33 and ZTK 33 illustrates the advantage of the ZTK diode. According to equation 6, the ZPD 33 at $I_Z = 5$ mA offers a static differential resistance of $r_{zu} = r_{zj} + r_{zth} = 40\ \Omega + 300\ \Omega = 340\ \Omega$.

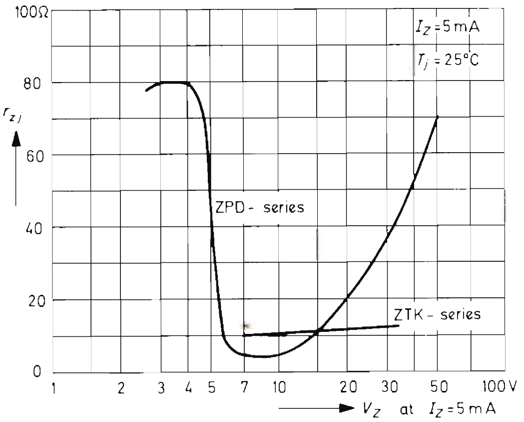


Fig. 40: Inherent dynamic resistance of ZPD and ZTK diodes

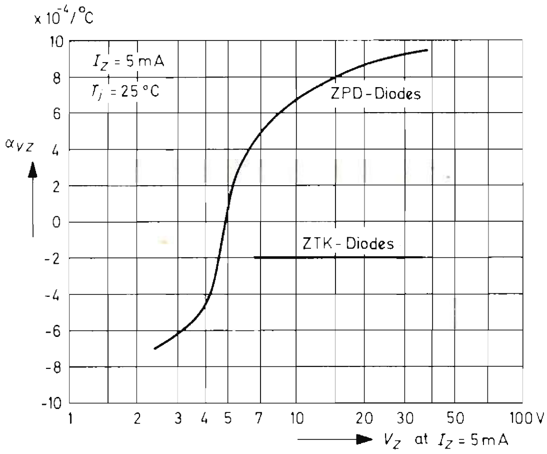


Fig. 41: Temperature coefficient of the operating voltage of ZPD and ZTK diodes

The values for r_{zj} and r_{zth} were taken from table 2 and Fig. 26 respectively. If we assume a supply voltage of 60 V and a load current of 2 mA, then, with $I_Z = 5$ mA, the series resistance in the circuit arrangement of Fig. 24 is

$$R_S = \frac{V_{in} - V_Z}{I_Z + I_{out}} = \frac{27\ \text{V}}{7\ \text{mA}} = 3.9\ \text{k}\Omega$$

and the stabilising factor according to equation 12, is

$$S = \left(1 + \frac{R_S}{r_{zu}}\right) \cdot \frac{V_Z}{V_{in}} = \left(1 + \frac{3900\ \Omega}{340\ \Omega}\right) \cdot \frac{33\ \text{V}}{60\ \text{V}} = 6.9\,.$$

For the ZTK 33, we obtain from equation 7 the thermal differential resistance

$r_{zth} = \alpha_{VZ} \cdot R_{thA} \cdot V_Z{}^2 = -2 \cdot 10^{-5}/^\circ C \cdot 400\ ^\circ C/W \cdot 1090\ V^2,$

and

$r_{zu} = r_{zi} + r_{zth} = 10\ \Omega - 8.7\ \Omega = 1.3\ \Omega$

and the stabilising factor is

$$S = \left(1 + \frac{R_S}{r_{zu}}\right)\frac{V_Z}{V_{in}} = \left(1 + \frac{3900\ \Omega}{1.3\ \Omega}\right) \cdot \frac{33\ V}{60\ V} = 1650\,.$$

Thus, S is 240 times higher than in the case of the ZPD 33! In both cases the calculation was based on typical values and no worst-case calculations were carried out.

It only remains to see by what amount the voltage in the circuit arrangement of Fig. 24 under consideration varies as a result of a 25 °C change of temperature. In the case of the ZPD 33, the temperature coefficient of the operating voltage $\alpha_{VZ} = 9 \cdot 10^{-4}/^\circ C$ and the operating voltage varies by

$$\Delta V_Z = \Delta\, T_j \cdot \alpha_{VZ} \cdot V_Z\,, \qquad (36)$$

which, in numerical values, reads

$\Delta V_Z = 25\ ^\circ C \cdot 9 \cdot 10^{-4}/^\circ C \cdot 33\ V = 0.74\ V$

or, relatively, +2.5 %.

In the case of the ZTK we obtain

$\Delta V_Z = 25\ ^\circ C \cdot (-2 \cdot 10^{-5}/^\circ C) \cdot 33\ V = -0.0165\ V$

or, relatively, −0.05 %. Even if, according to a worst-case consideration the extreme spread of the temperature coefficient ($-10 \ldots +5 \cdot 10^{-5}/^\circ C$) were taken into account, the least favourable variation of the operating voltage to be anticipated would, in relative terms, be −0.25 %, i. e. still better by one order of magnitude than in the case of the ZPD 33.