United States Patent

[11] 3,621,446

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[54] **THERMAL RELAY**
9 Claims, 2 Drawing Figs.

[52] **U.S. Cl.** **338/23**
[51] **Int. Cl.** **H01c 7/04**
[50] **Field of Search** 338/20, 23, 24, 25

[56] **References Cited**
UNITED STATES PATENTS

1,631,836 6/1927 Spray 338/20

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ABSTRACT: In a thermal relay of the type using a conductive heater layer to switch a layer of vanadium dioxide between nonconducting and conducting states, design advantages are attained by using a conductive substrate separated from the vanadium dioxide by a layer of insulative material having a thermal conductance per unit area that is within certain prescribed limits.

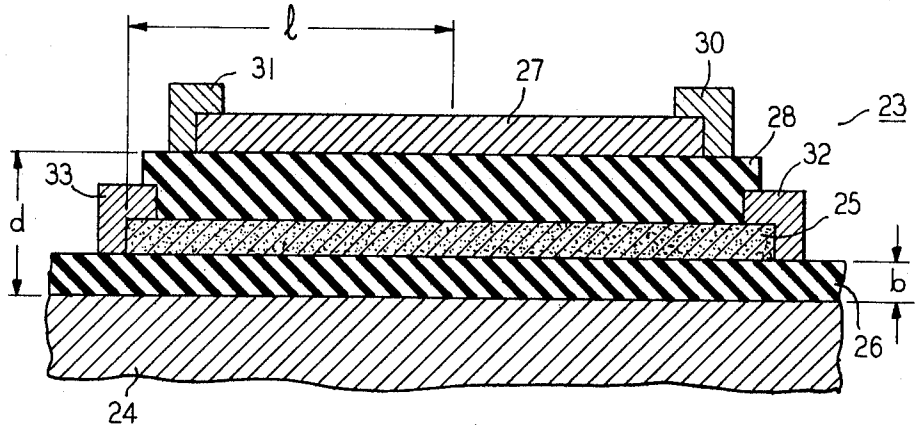


FIG. 1
PRIOR ART

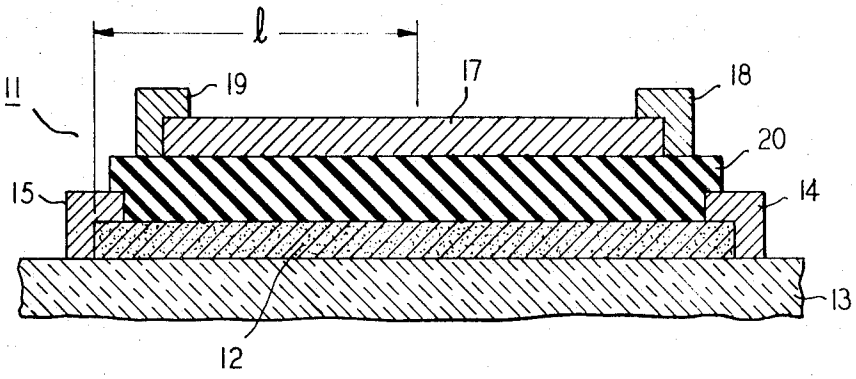
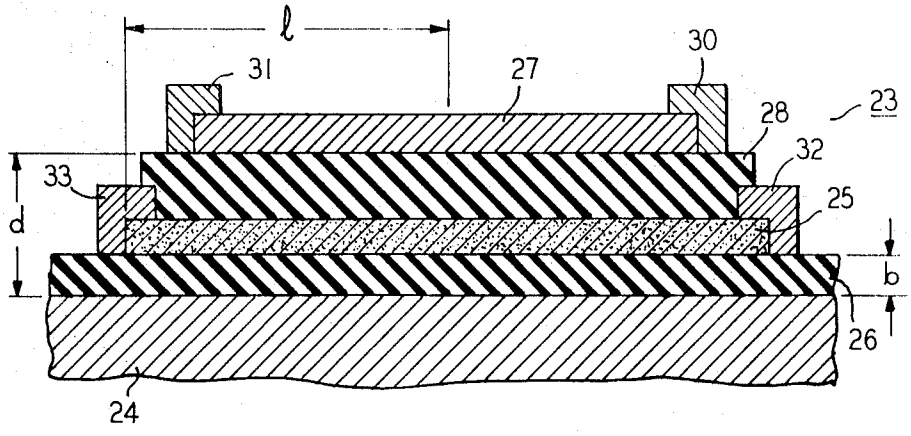


FIG. 2



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THERMAL RELAY

BACKGROUND OF THE INVENTION

This invention relates to relays, and more particularly, to relays that make use of the negative temperature coefficient of resistivity of material such as vanadium dioxide.

The paper "Thin-Film Switching Elements of VO_2" by K. van Steensel, F. van de Burg and C. Kooy, Philips Research Reports, Volume 22, pages 170–177, 1967, describes a four-terminal relay in which a conductive heater film is used to switch a layer of vanadium dioxide between conducting and nonconducting states. Vanadium dioxide is an example of a material which, because of its negative temperature coefficient of resistivity, will act as a low resistivity metal if heated above a threshold temperature, but will act as a high resistivity semiconductor if maintained at a temperature below the threshold. The relay structure described by van Steensel et al. comprises a layer of vanadium dioxide on an insulative substrate such as glass, an insulative film such as silicon oxide overlaying the vanadium dioxide, and a conductive heater film overlaying the silicon oxide layer. By passing current through the heater layer, the vanadium dioxide is switched from a nonconducting to a conducting state in which it transmits current between opposite contacts.

It is of course desirable to optimize the operating parameters of the van Steensel et al. relay to conform to the systems in which it is to be used. In particular, it is often desirable to optimize the power required for switching and the time required for switching. These two parameters, however, are mutually dependent and one cannot be changed without changing the other.

SUMMARY OF THE INVENTION

It is an object of this invention to provide a thermal relay in which the power required for switching and the time required for switching can be substantially independently designed.

This and other objects of the invention are attained in an illustrative embodiment thereof comprising a thermal relay of the general type described above. Rather than using an insulative substrate, however, a thermally conductive substrate is used which is separated from the vanadium dioxide layer by a thin layer of insulative material. The thermal conductance of the insulative layer is maintained within a specified range such that a thermal path is provided from the heater film through the vanadium dioxide layer to the conductive substrate. With this provision it can be shown that the power P required for switching and the time t required for switching can be optimized independently of each other. Since any desired switching time t and any desired switching power P can, within a rather broad range, be attained, the flexibility and number of uses to which the relay may be put are substantially increased.

These and other objects, features and advantages of the invention will be better understood from a consideration of the detailed description taken in conjunction with the accompanying drawing.

DRAWING DESCRIPTION

FIG. 1 is a sectional view of a thermal relay of the prior art; and

FIG. 2 is a sectional view of a thermal relay in accordance with an illustrative embodiment of the invention.

DETAILED DESCRIPTION

Referring now to FIG. 1, there is shown a thermal relay **11** of the type described in the van Steensel et al. paper comprising a layer **12** of vanadium dioxide (VO_2) having contacts **14** and **15** on opposite ends and bonded to a substrate **13** of insulative material. A conductive heater film **17** having contacts **18** and **19** is located in close proximity to the VO_2 layer but is insulated from it by a layer **20** of insulative material.

When the VO_2 layer **12** is below a threshold temperature, typically 68° C., it acts as a semiconductor and displays a high resistivity to current between contacts **14** and **15**. When the layer **12** is heated above its threshold temperature, due to heat generated by heater film **17**, it acts as a low resistivity metal, and current flows freely between opposite contacts. Thus the structure of FIG. **1** constitutes a four-terminal thermal relay: When current is directed through heater film **17**, the temperature of the VO_2 layer **12** is raised above threshold and current is transmitted through a circuit including contacts **14** and **15**; but, when current through the heater film **17** is terminated, current through the VO_2 layer is substantially reduced.

Of course, numerous four-terminal relay devices other than that shown in FIG. **1** are available to the engineer designing a system, and the one he chooses will significantly depend on the extent to which device parameters can be optimized to match the requirements of the system. Two parameters that characterize the device of FIG. **1** are the power P′ required by the heater film **17** to switch the VO_2 layer between conductive states, and the time t′ required for such switching. It can be shown that the switching power P′ of the FIG. **1** device is given by the equation

$$P' = (\pi^2 l K' \Delta T/2) \quad (1)$$

and the switching time t' is given by

$$t' = (l^2/4\alpha') \quad (2)$$

where K' is the thermal conductivity of substrate **13**, α' is the thermal diffusivity of the substrate, ΔT is the difference in temperature between the transition temperature and the ambient temperature, and l is half the lateral dimension of the VO_2 layer **12** as shown in FIG. **1**. Notice that only one geometrical parameter, namely the lateral dimension l, is contained in the expressions for P' and t'. Hence, switching power and switching time cannot be independently determined in the design of the structure, and compromises between the two are inherent.

In accordance with the invention, this drawback is overcome by the relay **23** of FIG. **2** which uses a conductive substrate **24** rather than an insulative substrate. The vanadium dioxide layer **25** is separated from the conductive substrate by an insulative layer **26**. A heater film **27** is separated from the VO_2 layer by an insulative layer **28**. As before, heater current between contacts **30** and **31** is used to switch the states of the VO_2 layer **25**, thereby controlling current between contacts **32** and **33**. Since the substrate **24** is a good conductor of heat, a thermal path is provided that extends from heater film **27** to the substrate. This thermal path will transmit a significant quantity of heat compared to that transmitted by the contacts if the thermal conductance of insulative film **26** is within a specified range and if the combined thickness d of insulative layer **28**, VO_2 layer **25** and insulative layer **26** is smaller than the lateral dimension l. When this is true, it can be shown that the power P required for switching is given by

$$P = (3\pi l^2 K \Delta T/8d) \quad (3)$$

and the switching time t is given by

$$t = (d^2/\alpha) \quad (4)$$

where K is the thermal conductivity of layer **26**, and α is the thermal diffusivity of layer **26**. Notice that in this case switching power P is a function of the lateral dimension l and the thickness dimension d while switching time t is a function only of the thickness dimension d shown in FIG. **2**. This being true, switching time and switching power can be independently optimized by independent adjustment of the dimensions l and d.

Substrate **24** should of course be made of a material having high thermal conductivity such as copper. The insulative layer **26** may conveniently be silicon dioxide which has a thermal conductivity of 10^{-7E-2} watts per centimeter-degree centigrade. Setting K equal to 10^{-7E-2}, table I shows various values of the thickness dimension d and the lateral dimension l that should be used for designing relays having switching powers of between 10^{-7E-1} and 10^{-7E-3} watts and switching times t of between 10^{-7E-3} and 10^{-7E-6} seconds, in accordance with equations (3) and (4):

TABLE I

d, l		t (sec.) Hi Speed	Lo Speed
(μm)		$10^{7E^{-6}}$	$10^{7E^{-3}}$
	Lo Power		
P	$10^{7E^{-3}}$	0.6, 2.4	17, 13
(watts)	Hi Power		
	$10^{7E^{-1}}$	0.6, 24	17, 130

The first number in each box refers to the thickness dimension d to be used and the second number to the lateral dimension l. For example, if a high speed low power relay is designed to have a switching time t of $10^{7E^{-6}}$ seconds and a switching power P of $10^{7E^{-3}}$ watts, the thickness dimension d should be 0.6 microns and the lateral dimension l should be 2.4 microns.

A useful parameter for characterizing the insulative layer **26** is the conductance per unit area G_A, which is related to the thermal conductivity K and thickness b by the equation

$$G_A = K/b \quad (5)$$

Assuming that $K \approx 10^{7E^{-2}}$ watts per centimeter degree C., table I defines a range of values for G_A assuming $d \approx b$, given by

$$5.9 \leq G_A \leq 170 \text{ watts/cm}^2\text{-°C.} \quad (6)$$

Materials having other values of thermal conductivity K could of course be used as the insulative film **26**, but is is unlikely that a material having a thermal conductivity of substantially less than $10^{7E^{-3}}$ or substantially more than $10^{7E^{-1}}$ watts/cm − °C. would be useful in a thermal relay. Assuming that k is $10^{7E^{-3}}$, the values of dimensions d and l are those given in table II:

TABLE II

d, l		t (sec.) Hi Speed	Lo Speed
(μm)		$10^{7E^{-6}}$	$10^{7E^{-3}}$
	Lo Power		
P	$10^{7E^{-3}}$	0.17, 4.0	5.0, 20
(watts)	Hi Power		
	$10^{7E^{-1}}$	0.17, 40	5.0, 200

Table II leads to the following range of values of G_A:

$$2.0 \leq G_A \leq 60 \text{ watts/cm}^2\text{- °C.} \quad (7)$$

Assuming that K is $10^{7E^{-1}}$ watts/cm-°C., the range of values for d and l is that given in table III.

TABLE III

d, l		t (sec.) Hi Speed	Lo Speed
(μm)		$10^{7E^{-6}}$	$10^{7E^{-3}}$
	Lo Power		
P	$10^{7E^{-3}}$	2.0, 1.6	60, 30
(watts)	Hi Power		
	$10^{7E^{-1}}$	2.0, 16	60, 300

Table III leads to the following range of values for G_A:

$$20 \leq G_A \leq 500 \text{ watts/cm}^2\text{ - °C.} \quad (8)$$

From relationships (7) and (8), a general range of values for the thermal conductance per unit area for any reasonable value of thermal conductivity may be defined as

$$2.0 \leq G_A \leq 500 \text{ watts/cm}^2\text{ - °C.} \quad (9)$$

Extensive mathematical analyses which could have been included for showing the derivation of the relationships given above have, for reasons of brevity and clarity, not been included. To simplify computation, these analyses assume a circular configuration of the various layers of the structures of both FIGS. **1** and **2**. To give a more general statement of the switching power P of the structure of FIG. **2** equation (3) may be expressed as

$$P = CAK\Delta T/d \quad (10)$$

where A is the area of VO_2 layer **25** and C is a constant dependent on device configuration which, in the case of a circular structure, is ⅝. The constant is nearly equal to ⅝ for structures that are nearly symmetrical such as square configurations.

In summary, the criteria defining a thermal relay structure in which the switching power and switching time are mutually independent have been established. The ability to adjust switching power and switching time independently substantially increases the uses to which relays of this type may be put. For example, the relay of FIG. **2** may be used as an average power limiter in which a low power threshold and long switching time are simultaneously required. Moreover, it can be shown that if both the switching power P and the time t are sufficiently small, the switching energy of the relay of FIG. **2** is substantially smaller than that of FIG. **1**. The ratio of switching energy e_1 of the relay of FIG. **2** to the switching energy e_2 of a comparable relay of FIG. **1** can be shown to be

$$e_1/e_2 \approx d/l \quad (11)$$

While the relay has been described as using a VO_2 layer, it is to be understood that any material having a negative temperature coefficient of resistivity could alternatively be used. Various other modifications and embodiments may be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A thermal relay comprising:
- a layer of resistive material having a resistivity that varies as a function of temperature and having contacts at opposite ends thereof;
- a conductive substrate on one side of the resistive layer and insulated therefrom by a first layer of insulative material;
- a conductive heater layer on the opposite side of the resistive layer and insulated therefrom by a second layer of insulative material;
- the first layer of insulative material having a thermal conductance per unit area G_A which is less than approximately 500 watts per centimeter^2 - degree centigrade.

2. The thermal relay of claim **1** wherein:
- the layer of resistive material has a negative coefficient of resistivity.

3. The thermal relay of claim **2** wherein:
- the parameter G_A in watts per centimeter^2 - degree centigrade substantially conforms to the relationship $2.0 \leq G_A \leq 500$.

4. The thermal relay of claim **3** wherein:
- the thermal conductivity K of the first layer of insulative material is approximately $10^{7E^{-1}}$ watts per centimeter - degree centigrade and the parameter G_A substantially conforms to the relation $20 \leq G_A \leq 500$.

5. The thermal relay of claim **3** wherein:
- the thermal conductivity K of insulative material is approximately $10^{7E^{-2}}$ watts per centimeter - degree centigrade and the parameter G_A substantially conforms to the relationship $5.9 \leq G_A \leq 170$.

6. The thermal relay of claim **3** wherein:
- the thermal conductivity K of the first layer of insulative material is approximately $10^{7E^{-3}}$ watts per centimeter - degree centigrade and the parameter G_A substantially conforms to the relationship $2.0 \leq G_A \leq 60$.

7. The thermal relay of claim **3** wherein:
- the first layer of insulative material is a silicon compound having thickness of between 0.17 and 60 microns.

8. The thermal relay of claim **7** wherein the first layer of insulative material is of silicon dioxide.

9. The thermal relay of claim **3** wherein:
- the length of the layer of resistive material is larger than the combined thickness of the resistive material layer of insulative material and the second layer of insulative material.

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,621,446 Dated November 16, 1971

Inventor(s) George E. Smith and Robert H. Walden

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Col. 2, line 69, $10^{'7E'2}$ should be 10^{-2};
line 70, $10^{'7E'2}$ should be 10^{-2};
line 73, $10^{'7E'1}$ should be 10^{-1};
line 73, $10^{'7E'3}$ should be 10^{-3};
line 74, $10^{'7E'3}$ should be 10^{-3};
line 74, $10^{'7E'6}$ should be 10^{-6};

Col. 3, TABLE I, under Hi Speed, $10^{'7E'6}$ should be 10^{-6};
under Lo Speed, $10^{'7E'3}$ should be 10^{-3};
under Lo Power, $10^{'7E'3}$ should be 10^{-3};
under Hi Power, $10^{'7E'1}$ should be 10^{-1};

Col. 3, line 16, $10^{'7E'6}$ should be 10^{-6};
line 17, $10^{'7E'3}$ should be 10^{-3};
line 24, $10^{'7E'2}$ should be 10^{-2};
line 31, $10^{'7E'3}$ should be 10^{-3};
line 31, $10^{'7E'1}$ should be 10^{-1};
line 33, $10^{'7E'3}$ should be 10^{-3};

Col. 3, TABLE II, under Hi Speed, $10^{'7E'6}$ should be 10^{-6};
under Lo Speed, $10^{'7E'3}$ should be 10^{-3};
under Lo Power, $10^{'7E'3}$ should be 10^{-3};
under Hi Power, $10^{'7E'1}$ should be 10^{-1};

Col. 3, line 50, $10^{'7E'1}$ should be 10^{-1};

FORM PO-1050 (10-69)

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* U.S. GOVERNMENT PRINTING OFFICE : 1969 O—366-334

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,621,446 Dated November 16, 1971

Inventor(s) George E. Smith and Robert H. Walden

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Col. 3, TABLE III, under Hi Speed, $10^{'7E'6}$ should be 10^{-6};
under Lo Speed, $10^{'7E'3}$ should be 10^{-3};
under Lo Power, $10^{'7E'3}$ should be 10^{-3};
under Hi Power, $10^{'7E'1}$ should be 10^{-1};

Col. 4, line 3 of claim 4, $10^{'7E'1}$ should be 10^{-1};
line 3 of claim 5, $10^{'7E'2}$ should be 10^{-2};
line 3 of claim 6, $10^{'7E'3}$ should be 10^{-3};
line 3 of claim 9, after "layer" insert
,the first layer.

Signed and sealed this 23rd day of May 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents