

ON-CHIP COMPENSATION OF SELF-HEATING EFFECTS IN MICROBOLOMETER INFRARED DETECTORS

BACKGROUND OF INVENTION

Technical Field of the Invention

This invention relates generally to a microbolometer
5 infrared detector arrays, and more particularly, to a
method and apparatus that compensates for the self-
heating effects during readout of a microbolometer.

Description of Related Art

In the last a few years, there has been a rapid
10 development of infrared focal plane arrays (FPA) using
uncooled microbolometers (Wood, "Uncooled Thermal Imaging
With Monolithic Silicon Focal Planes." Proc. SPIE, 1993,
vol. 2020, pp. 322-329 and Tanaka et al. "Infrared Focal
Plane Array Incorporating Silicon IC Process Compatible
15 Bolometer," IEEE Trans. on Electron Devices, vol. 43, pp.
1844-1860, 1996.

The typical microbolometer sensor essentially
consists of two components: (a) an IR absorber which is
usually a membrane, made of SiO_2 and/or Si_3N_4 , and (b) a
20 resistive temperature sensor fabricated using a material
with high temperature coefficient of resistance (TCR).

Incident infrared (IR) radiation heats the sensor
thereby changing its resistance which is read out using an
external circuit, for example, a Wheatstone bridge. The
25 sensor must be electrically biased in order to read the
amount of resistance change, which is usually done using a
voltage pulse as disclosed by H. Beratan et al. "Low-Cost
Uncooled Ferroelectric Detector," Integr. Ferroelectric,
vol. 4, pp. 175-186 (1994).

30 Thus, the sensor will be heated not only by the
absorbed infrared radiation, but also by self-heating
caused by the external current applied to the resistive
sensor element during the read-out. This self-heating is

typically much greater than the heating due to the incident IR radiation to be detected.

If no compensation is performed for the self-heating effect, a large portion of the dynamic range in the succeeding readout circuitry must be sacrificed to prevent saturation. This results in a decrease in temperature resolution of the sensor or increase in complexity in the design of readout circuitry needed to meet a specific performance. In order to avoid extra signal conditioning design challenges or degradation of performance, some form of on-chip compensation is of considerable interest.

Recently, Jansson et al. "Theoretical Analysis of Pulse Bias Heating of Resistance Bolometer Infrared Detectors and Effectiveness of Bias Compensation," Proc. SPIE, 1995, vol. 2552, pp. 644-652 proposed techniques using active off-chip circuitry to compensate for the self-heating effect. In this method, an on-chip sensor detects the temperature increase of the microbolometer in the form of a resistance change during read-out, and off-chip circuits produce a voltage ramp to compensate for the self-heating effect.

This conventional self-compensation has certain disadvantages such as the required off-chip circuits that increase complexity and costs while reducing reliability.

SUMMARY OF THE INVENTION

This invention provides a self-heating compensation technique during readout of bolometer arrays. One of the advantages of the inventive techniques is that no off-chip circuits are involved and all the compensation is done on-chip using passive components. More importantly, the invention's circuit configuration is compatible with the standard focal plane array (FPA) technology and hence it can be implemented without any significant alteration to the fabrication process.

During the inventive process, the thermal and electrical behaviors of the microbolometer were modeled

and then analytical and numerical solutions provided in order to understand how the different parameters affect the detector's self-heating. On the basis of these investigations, a new on-chip compensation scheme is
5 proposed and its effectiveness is analyzed by numerical simulations. The validity of the model was confirmed by studying microbolometers under pulse bias condition. Finally, a circuit configuration for the implementation
10 of this compensation technique for FPAs applications is discussed.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific
15 examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

20 **BRIEF DESCRIPTION OF THE DRAWINGS**

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limitative
25 of the present invention, and wherein:

Figure 1 (a) illustrates a balanced bridge readout circuit where R_B represents the bolometer resistance and R_0 and R_{ref} represent reference resistors;

Figure 1(b) is a thermal model for a microbolometer,
30 where H denotes the thermal capacitance and G thermal conductance;

Figure 2 is a scanning electron microscope photograph of one of the microbolometers used in the study of self-heating effects which has a measured
35 thermal conductance of about 5×10^{-5} J/W;

Figure 3(a) is a graph of measured output voltages (open circles) of the bridge circuit using a single bolometer and three fixed resistors by applying 8 V pulses to the bridge with 2 μ s duration at 30 Hz;

5 Figure 3(b) is a graph of measured output voltages (triangles) of the bridge circuit using two microbolometers (sensing and reference) with nearly the same parameters as Figure 3(a) except that the reference
10 microbolometer has a larger thermal conductance than the sensing microbolometer; and

Figure 4 is a schematic circuit configuration of a bolometer array with one row of reference bolometers having larger thermal conductance than the sensing bolometers to compensate for the self-heating effects.

15 **DETAILED DESCRIPTION OF THE INVENTION**

Before turning to the details of the present invention, a brief review of the modeling and analysis techniques utilized by the inventors is appropriate.

Modeling and Analysis

20 In the succeeding analysis, it is assumed that the resistance change of the bolometer is read using a Wheatstone bridge configuration as illustrated in Fig. 1(a). In the case of a focal plane array (FPA), different bolometers can be connected sequentially to the bridge
25 using a multiplexing circuit.

From the start to the end of readout period, t_{bias} , a given bolometer is biased. This biasing causes a rapid increase of temperature, from T_0 to T_{bias} , due to the Joule heating, where, T_0 is the ambient temperature. The
30 readout duration of a bolometer is approximately equal to the frame readout time over the number of bolometers.

At the end of the readout period, the bolometer starts to cool down via thermal conductance to the surroundings at a rate determined by the thermal time
35 constant. During the readout, the total power gain of the bolometer, P , is a sum of the self-heating power, P_{bias} ,

and the absorbed infrared radiation power, P_{rad} . Both of these components contribute to the temperature rise of the bolometer.

As is conventional, the thermal behavior of a bolometer can be modeled using a circuit consisting of heat capacitance, H , and thermal conductance, G , as illustrated in Fig. 1 (b). The changing bolometer resistance, R_d , due to the temperature rise can be approximated by the following equation:

$$R_d = R_0(1 + \alpha(T - T_0)) \quad (1)$$

where R_0 is the resistance of the bolometer at ambient temperature and α is the temperature coefficient of resistance (TCR). The temperature variation of the bolometer as a function of time is given by

$$H \frac{dT}{dt} = P_{bias} + P_{rad} - G(T - T_0) \quad (2)$$

This is the heat balance equation stating that the difference between the sum of powers from pulse bias and incident infrared radiation and the power dissipation through the thermal conductance (G) will give the rate of temperature change determined by the heat capacitance, H .

In the subsequent analysis, it is assumed the incident IR radiation power, $P_{rad} = 0$, since our interest is reducing the self-heating effect. The changes in the temperature, resistance and voltage across the bolometer are relatively small during the operation compared to their corresponding absolute values. Thus the bias power can be approximated as

$$P_{bias} \approx \frac{V_B^2}{4R_0} \quad (3)$$

where V_B is the bias voltage applied across the bridge during the readout. At room temperature, the values of

the four resistors are assumed to be equal. Since in practice, the thermal time constant $\tau = \frac{H}{G}$ is about several milliseconds, while read-out time (t_{bias}) is only a few microseconds, the temperature rise of the bolometer during the readout can be approximated using Eqns. (2) & (3) as,

$$\Delta T \approx \frac{V_B^2}{4R_0 H} t \quad (0 < t < t_{bias}) \quad (4)$$

Thus, the output voltage of the bridge circuit can be obtained using the TCR, $\alpha = \frac{\Delta R}{R \Delta T}$ as follows,

$$\Delta V_{out} \approx \frac{\alpha V_B^2}{16R_0 H} t \quad (0 < t < t_{bias}) \quad (5)$$

To estimate the extent of the self-heating effect on the signal output, one may calculate the voltage across the bridge using the parameters given by Tanaka et al. cited above where $V_B = 5$ V, $H = 1.7 \times 10^{-9}$ J/K, $\alpha = 0.25\%/K$, $R_0 = 3.4$ k Ω and $t = 2$ μ s. The calculated value of the voltage generated by the self-heating using Eqn. 5 is about 9 mV. However, the signal due to incident IR radiation (typically about 100 nW) is only about 0.7 mV for typical responsivity of 70,000 V/W. This is an order of magnitude smaller than the signal due to self-heating.

Thus, a large portion of the dynamic range of the preamplifier will have to be sacrificed by the output voltage associated with the self-heating. This leaves only a small portion of the dynamic range for measuring the incident IR resulting in a poor image quality.

One of the simplest ways to compensate the self-heating effect is to use an identical array of reference bolometers located next to each measuring array of sensors that act as reference resistors in the Wheatstone bridge. This approach is not practical due to drastic

reduction of the fill factor of the array and more importantly, cancellation of the infrared signals generated in the sensor and reference bolometers.

On the other hand, a single bolometer can not be
5 used as reference since it will be biased continuously and the resultant self-heating will necessarily be much larger than that of sensors which are exposed to the bias for only a few microseconds.

However, it was noted by the inventors from Eqn. 5
10 that the self-heating effect is independent of the thermal conductance (G) as long as the readout time is much smaller than the thermal time constant (H/G) of the bolometer. Thus, if a bolometer with a higher thermal conductance is used as the reference it will not only be
15 insensitive to the incident infrared but also can be addressed at a higher rate compared to the sensors. This prompted the inventors to explore using a single column of reference bolometers that are addressed once during the readout of each row of the sensor array. In the
20 following, this concept will be demonstrated experimentally using two bolometers arranged in a Wheatstone bridge.

Experimental Demonstration of Inventive Concepts

The following is an explanation of experimental
25 results demonstrating the self-heating compensation according to the invention. In the experiments, two bolometers were fabricated by standard CMOS technology but with the inventive design. In addition, a scheme to implement the self-heating compensation on-chip for a
30 focal plane array of bolometers is also discussed.

The structure of the bolometer consists of a composite film of $\text{SiO}_2/\text{Si}_3\text{N}_4$ membrane and a Ti meander line resistor as the sensor. Figure 2 shows a scanning electron micrograph (SEM) picture of one of the
35 bolometers.

The room temperature resistance of the bolometers is about $7\text{ k}\Omega$ while the heat capacitance is about $2 \times 10^{-9}\text{ J/K}$. The thermal conductance of the bolometers is varied between $5 \times 10^{-5}\text{ W/K}$ and $5 \times 10^{-7}\text{ W/K}$ by adjusting the dimensions of the membrane attachment with the substrate.

To demonstrate the self-heating effect, a bolometer is first connected to a Wheatstone bridge using three fixed reference resistors with resistance of about $7\text{ k}\Omega$ each. Then the bridge is biased using voltage pulses of 5V with $40\text{ }\mu\text{s}$ duration at 30 Hz, which is a typical frame rate used for bolometer FPAs.

Figure 3(a) shows the output of the bridge measured with a digital oscilloscope. The linear slope on the step clearly shows the change in resistance of the bolometer due to the self-heating effect. Note that the positive voltage pulse is due to the slight difference in values of the reference resistors in the bridge.

To illustrate the inventive compensation scheme, the bridge is rearranged using two bolometers along with two fixed reference resistors. The output voltage is again observed using the pulses similar to the previous case and the result is shown in Fig. 3(b). It can be clearly seen that the voltage ramp observed in Fig. 3(a) mostly disappears. This is due to the fact that both bolometers experienced the same temperature rise during the readout.

ON-CHIP COMPENSATION

A preferred FPA circuit configuration 100 with on-chip compensation using a balanced resistor bridge readout mechanism is illustrated in Fig. 4. The resistors labeled R_B represent the resistances of the microbolometers in the array. The reference bolometers (R_{ref}) with higher thermal conductance than the sensing microbolometers are arranged in a row adjacent to the sensor array.

As further shown in Figure 4, circuit 100 includes an array of sensing microbolometers indicated by R_B

arranged adjacent to a row of reference bolometers indicated by R_{ref} . Each resistor R_B is connected to ground via a sensor selecting switch 105 such as the pixel MOSFET shown in Figure 4. Each resistor R_B is also
5 connected to a corresponding sensor column switch 115.

The control input or gate of each sensor selecting switch 105 is connected to a corresponding bit of a Y-shift register 110. The control input or gate of each sensor column switch 115 is connected to a corresponding
10 bit of an X-shift register 120.

The outputs of the sensor column switches 115 are connected to a Wheatstone bridge that includes a bias voltage V_B input and two resistors of known and equal values R_0 . Thus, the selected output of the sensor column
15 switches 115 form a leg of this bridge with resistance R_B .

The reference bolometer resistances R_{ref} are individually connected to ground via a corresponding reference selecting switch 125 such as the reference selecting MOSFET shown in Figure 4. Each resistor R_{ref} is
20 also connected to a corresponding reference column switch 125.

The control input or gate of each reference selecting switch 125 is connected to V_{DD} . The control input or gate of each reference column switch 135 is
25 connected to a corresponding bit of the X-shift register 120.

The outputs of the reference column switches 135 are connected to the Wheatstone bridge. Thus, the selected output of the reference column switches 135 form the last
30 leg of this bridge with resistance R_{ref} .

The multiplexing operation of the circuit 100 is carried out in the following manner to select the sensor and reference bolometers to form the Wheatstone bridge. First, a row of the sensing array is selected using the
35 Y-shift register 110 and then a particular sensor and the corresponding reference bolometer are simultaneously selected using the X-shift register.

The circuit 100 is wired as described above such that whenever a sensor bolometer is selected, the reference bolometer on the same column is also selected. The outputs of the sensor and reference column switches
5 115, 135 are wired to two fixed reference resistors R_0 to complete the bridge and a bias voltage V_B is applied across the bridge as shown in Fig. 4.

By using this configuration, a resistor bridge circuit can be formed momentarily for each bolometer in
10 the array during a scan. Then, any differences between R_B and R_{ref} can be read-out at the output of the differential pre-amplifier 150.

Because the thermal capacitance of the reference bolometers is same as the sensor bolometers, the
15 temperature ramps generated by both the sensor and reference bolometers are nearly the same during the readout.

Note that the presence of slow varying incident IR does not change the resistance R_{ref} of the reference
20 bolometer due to its large thermal conductance. The advantageous result is that the output voltage V_{out} from the resistor bridge is mainly due to the change of resistance R_B of the sensor bolometers caused by the incident IR radiation without the self-heating effects.

In order to achieve self-heating compensation effectively, the reference bolometers must have relatively large thermal conductance compared to the detectors. When a detector or reference resistor cools
25 down its temperature as a function of time can be described by Eqn. 1 setting both P_{bias} and P_{rad} equal to zero. In this case, the solution is given by
30

$$T(t) = T_b e^{-t/\tau} \quad (6)$$

where T_b is the temperature of the bolometer at the end of the readout period. It can be seen that the thermal time
35 constant $\tau = H/G$ determines the rate of cooling.

Because there is only one row of reference resistors, while there is a large number of sensing bolometer rows (N_{row}) in the chip, the cooling rate of the reference resistors should be at least be N_{row} times faster than that of the sensors. If the reference bolometer has the same thermal time constant as the sensors, it can not cool down completely within the row readout period (t_{frame}/N_{row}) before it is biased again during the readout of the next row of sensors.

This can be overcome by reducing the thermal time constant of the reference bolometers. This is achieved by increasing the thermal conductance of the reference bolometers. For a microbolometer, the largest possible value of its thermal conductance is when it is not isolated from the substrate.

By not isolating the microbolometer from the substrate and keeping the microbolometer in thermal contact with the substrate, the thermal conductivity is determined by the membrane which is usually a composite film of SiO_2 and Si_3N_4 layers. Using the values of thermal conductivity of these materials, the thermal conductivity of the membrane was estimated to be about 0.014 W/K.cm. Considering a typical area of $50 \times 50 \mu m^2$ and 1 μm thick membrane, the value of G was estimated to be about 3.5×10^{-3} W/K.

On the other hand, the heat loss of a completely isolated bolometer is determined solely by the radiation loss to the environment. According to the Stefan-Boltzman Law, the thermal conductance due to the radiation can be obtained as follows,

$$G_{rad} = \frac{\eta \sigma A \{T(t)^4 - T_0^4\}}{T(t) - T_0} \quad (7)$$

where η is the emissivity, σ is Stefan's constant (5.6703×10^{-8} (W/m²)K⁴), A the exposed area of the bolometer and T the temperature.

For the dimensions of the bolometers discussed above, the lower bound of the thermal conductance is about 1.5×10^{-8} W/K. These upper and lower limits of G indicate that a reference resistor with desired thermal
5 time constant can be easily fabricated by controlling the dimension of the membrane attachment to the substrate. In general, the attachment area of the reference bolometer to the substrate can be controlled relative to the attachment area of the sensing bolometer. To achieve
10 the desired self-compensation effect, the attachment area of the reference bolometer should be larger than the attachment areas of the sensing bolometer.

The test bolometers that have been fabricated clearly show the possibility of controlling the thermal
15 conductance in the desired range.

In addition to the self-heating compensation for bolometer arrays, it is also possible to apply this technique for self-heating compensation for a single bolometer. Single bolometers are typically used in, for
20 example, contactless thermometers. If an identical bolometer is used for compensation as in the conventional art, it should be shielded from the incident infrared radiation so that the signal will not be canceled.

However, if a bolometer according to the teachings
25 of this invention is utilized no such shielding is necessary. More particularly, if a reference bolometer with higher thermal conductance than the sensing bolometer is utilized, the self-heating correction can be achieved without the otherwise-necessary shielding.

30 In this case, the ratio of the two thermal conductances, k , determines the degree of compensation which is strongly dependent on the ratio of read-out time (t_{bias}) to the thermal time constant (τ). For a given application, the optimum ratio of thermal conductances
35 can be estimated by considering the temperature changes due to the incident infrared power P_{rad} and self-heating using the following equation:

$$k^2 = \frac{P_{rad} 8R_0}{V_B^2} \left(\frac{\tau}{t_{bias}} \right)^2 \quad (8)$$

Typically, the conductance ratio should range between 10 to 100 depending on the strength of the infrared power and bias used for the read-out.

5 The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled
10 in the art are intended to be included within the scope of the following claims.



CLAIMS

- 1 1. A method of compensating for the self-heating
2 effects of a bolometer, comprising the steps of:
3 receiving IR radiation with a sensing bolometer,
4 receiving the IR radiation with a reference
5 bolometer,
6 measuring the IR radiation by comparing a resistance
7 of the sensing bolometer against a resistance of the
8 reference bolometer,
9 wherein the reference bolometer has a thermal
10 conductance sufficiently greater than a thermal
11 conductance of the sensing bolometer to compensate for
12 the self-heating effect in the sensing bolometer caused
13 by said measuring step.
- 1 2. The method according to claim 1,
2 said receiving steps receiving IR radiation during a
3 readout interval.
- 1 3. The method according to claim 1,
2 said measuring step including the step of applying a
3 bias voltage pulse to the sensing and reference
4 bolometers during a readout interval.
- 1 4. The method according to claim 2, further comprising
2 the step of:
3 adjusting the relative thermal conductances of the
4 reference and sensing bolometers.
- 1 5. The method according to claim 4, further
2 comprising the step of:
3 attaching the reference and sensing bolometers to
4 a substrate with first and second attachment areas,
5 respectively,
6 said adjusting step including the substep of
7 controlling the first and second attachment areas such



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8 that the first attachment area is larger than the
9 second attachment area.

1 6. A self-heating compensated bolometer array,
2 comprising:
3 an array of sensing bolometers,
4 a row of reference bolometers arranged adjacent to
5 said array of sensing bolometers,
6 said reference bolometers having a larger thermal
7 / conductance than a thermal conductance of said sensing
8 bolometers,
9 means for selecting one of said sensing bolometers
10 and one of said reference bolometers,
11 a Wheatstone bridge circuit biased by a voltage
12 pulse during a readout interval, said Wheatstone bridge
13 circuit including two reference resistors, a resistance
14 of the selected sensing bolometer and a resistance of the
15 selected reference bolometer.

1 7. The self-heating compensated bolometer array
2 according to claim 6,
3 said array of sensing bolometers including only one
4 row of sensing bolometers.

1 8. The self-heating compensated bolometer array
2 according to claim 6,
3 said array of sensing bolometers including a
4 plurality of rows of sensing bolometers.

1 9. The self-heating compensated bolometer array
2 according to claim 6,
3 said selecting means sequentially selecting an
4 individual one of said sensing bolometers and a
5 corresponding one of said reference bolometers.

1 10. The self-heating compensated bolometer array
2 according to claim 6,
3 said Wheatstone bridge circuit including a
4 differential amplifier.



- 1 11. A method of fabricating a self-heating compensated
2 contactless thermometer that does not require a covering
3 for a reference bolometer, comprising the steps of:
4 fabricating a sensing bolometer on a substrate,
5 fabricating a reference bolometer on the substrate
6 having a thermal conductance that is larger than a
7 thermal conductance of the sensing bolometer, and
8 disposing the substrate in a thermometer housing.
- 1 12. The method according to claim 11,
2 said fabricating steps controlling the thermal
3 conductances of the reference and sensing bolometers by
4 controlling a degree of thermal contact of the reference
5 bolometer with the substrate relative to a degree of
6 thermal contact of the sensing bolometer with the
7 substrate.
- 1 13. A method of compensating for the self-heating
2 effects of a focal plane array of sensing bolometers,
3 comprising the steps of:
4 fabricating a row of reference bolometers having a
5 thermal conductance that is larger than a thermal
6 conductance of sensing bolometers,
7 disposing the row of reference bolometers adjacent
8 to the focal plane array of sensing bolometers,
9 sequentially measuring a resistance change of each
10 sensing bolometer against a corresponding one of the
11 reference bolometers.
- 1 14. The method according to claim 13,
2 said fabricating step controlling the reference
3 bolometer's conductance by controlling a degree of
4 thermal contact with an underlying substrate.
- 1 15. The method according to claim 13, further comprising
2 the step of:
3 fabricating the focal plane array of sensing
4 bolometers,



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5 said fabricating the focal plane array of sensing
6 bolometers step controlling the conductance of each
7 sensing bolometer by controlling a degree of thermal
8 contact with an underlying substrate such that the
9 thermal conductance of each sensing bolometer is lower
10 than the thermal conductance of each reference bolometer.

1 16. The method according to claim 13,
2 said sequentially measuring step addressing the row
3 / of reference bolometers once during the readout of each
4 row of the focal plane array of sensing bolometers.

1 17. A focal plane array architecture for selecting
2 reference bolometers to compensate for self-heating
3 effects of a microbolometer array, comprising:
4 an array of switching elements wherein each row of
5 said array of switching elements is commonly controlled
6 by a row select signal,
7 wherein each switching element in said array of
8 switching elements provides a controlled connection
9 between a corresponding resistance of the microbolometer
10 array and ground,
11 means for sequentially supplying the row select
12 signals to each row of said array of switching elements,
13 a row of reference bolometers,
14 a sensing circuit connected to a bias voltage and to
15 a selected one of said reference bolometers and a
16 selected one of the microbolometer array elements,
17 said sensing circuit detecting a change in
18 resistance of the selected microbolometer array element
19 due to infrared radiation incident thereon, wherein said
20 selected reference bolometer compensates for self-heating
21 effects in the selected microbolometer array element,
22 a plurality of sensor column switches sequentially
23 connecting corresponding columns of the microbolometer
24 array to said sensing circuit,
25 a plurality of reference column switches
26 sequentially connecting a corresponding reference



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27 bolometer to said sensing circuit during a readout
28 interval,

29 means for sequentially supplying column select
30 signals to said sensor and reference column switches.

1 18. The focal plane array architecture according to
2 claim 17, wherein each reference bolometer has a larger
3 thermal conductance than a thermal conductance of each
4 microbolometer array element.

1 19. The focal plane array architecture according to
2 claim 17,
3 said sensing circuit including a differential
4 amplifier for amplifying the sensed resistance change.

1 20. The focal plane array architecture according to
2 claim 17,
3 said sensing circuit including a Wheatstone bridge
4 circuit configuration having two resistors of equal
5 resistance values.