Methods for forming sensors using transition edge sensors (TES) and sensors therefrom are described. The method includes forming a plurality of sensor arrays includes at least one TES device. The TES device includes a TES device body, a first superconducting lead contacting a first portion of the TES device body, and a second superconducting lead contacting a second portion of the TES device body, where the first and second superconducting leads separated on the TES device body by a lead spacing. The lead spacing can be selected to be different for at least two of the plurality of sensor arrays. The method also includes determining a transition temperature for each of the plurality of sensor arrays and generating a signal responsive to detecting a change in the electrical characteristics of one of the plurality of sensor arrays meeting a transition temperature criterion.

10 Claims, 8 Drawing Sheets
FIG. 1A

100
FIG. 2

\( T_c(I, L) \)

\[
\begin{align*}
\square & \quad I = 10 \text{nA} \\
\circ & \quad I = 100 \text{nA} \\
\times & \quad I = 1 \mu\text{A} \\
\# & \quad I = 10 \mu\text{A} \\
\diamond & \quad I = 100 \mu\text{A}
\end{align*}
\]
BEGIN 302

SPECIFY DESIGN PARAMETERS FOR TES DEVICE 304

DEFINING A TES DEVICE BODY INCLUDING A NORMAL METAL LAYER 306

DEFINING SUPERCONDUCTING LEADS CONTACTING THE BODY, WHERE THE LEADS ARE SEPARATED BY AN INITIAL SPACING 308

ADJUSTING THE SPACING AND OTHER TES DEVICE PARAMETERS TO PROVIDE A TRANSITION TEMPERATURE FOR THE TES DEVICE THAT MEETS A TRANSITION TEMPERATURE CRITERIA 310

GENERATE DESIGN FOR FABRICATING TES DEVICES 312

RETURN 314

FIG. 3 300
BEGIN 402

FORM A PLURALITY OF SENSOR ARRAYS WITH VARIOUS AMOUNTS OF LEAD SPACING 404

DETERMINE A TRANSITION TEMPERATURE OF EACH OF THE SENSOR ARRAYS 406

MONITORING THE ELECTRICAL CHARACTERISTICS A SENSOR ARRAY MEETING A TRANSITION TEMPERATURE CRITERIA 408

SIGNALING A CHANGE IN TEMPERATURE IN RESPONSE TO DETECTING A CHANGE IN THE ELECTRICAL CHARACTERISTICS OF THE MONITORED SENSOR ARRAY 410

END 412

FIG. 4

400
SUPERCONDUCTING TRANSITION EDGE SENSORS AND METHODS FOR DESIGN AND MANUFACTURE THEREOF

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Patent Application Ser. No. 61/182,782, entitled “NOVEL SUPERCONDUCTING TRANSITION EDGE SENSOR DESIGN,” filed Jun. 1, 2009, which is herein incorporated by reference in its entirety.

This application is related to co-pending U.S. patent application Ser. No. 12/789,937, entitled “SUPERCONDUCTING TRANSITION EDGE SENSORS AND METHODS FOR DESIGN AND MANUFACTURE THEREOF,” filed concurrently herewith.

BACKGROUND

1. Technical Field

The present disclosure relates to sensors, and more specifically, to superconducting transition edge sensors and methods for design and manufacture thereof.

2. Introduction

A wide variety of particle detectors, energy detectors, and other devices can be made using a superconducting transition edge sensor (TES) as a thermal energy sensor, thermometer, bolometer, or microcalorimeter. By operating the device such that the TES is in the superconducting transition temperature region (i.e., the temperature region in which the material switches from normal conducting properties to superconducting properties) any heat deposited in the TES can be precisely measured due to the strong dependence of its electrical resistance on the temperature. Thus, very precise measurements of temperature changes and/or detection of an incident particle providing even minute heating, can be performed. The device can also be used as a high resolution thermometer with the energy of the absorbed particle determined by the measured heat pulse in the detector (when used as a microcalorimeter) or a change in absorbed power when a flux of particles are detected (when used as a bolometer). Manifestation of devices include a single TES thermally connected to a single particle absorbing material, a single TES thermally connected to multiple absorbers, or multiple TESs thermally connected to a single absorber body, it is also possible for the TES sensor to act as both the thermometer and absorber. Considerations when selecting an absorber material and absorber design is chosen such that it efficiently absorbs the particle of interest, has a sufficiently fast thermalization time to meet timing requirements, is compatible connecting with the TES body, and a heat capacity large enough such that heat pulses from particles of highest energy do not saturate but no so large that the energy resolution is sufficiently degraded.

Several conventional methods for fabricating TES-based detectors are available. For example, a TES device with a body consisting of a uniform superconductor material, having a target superconducting transition temperature \( T_c \) corresponding to the temperature of interest can be fabricated. In another method, the superconductive materials can be doped with magnetic impurities. In such devices, the concentration of magnetic particles is used to modify the \( T_c \) of the superconducting material being used for the body. In another method, the body of the TES device can be formed using a bilayer structure consisting of a normal metal layer (i.e., a metal layer that is not superconducting at the operating temperatures of interest when in isolation) disposed on a superconductor layer formed on a supporting substrate. Such devices take advantage of the proximity effect. That is, when a clean interface is provided between a superconducting film and a normal metal film, and the films are thinner than their coherence lengths, the bilayer acts as a single superconducting film with a transition temperature suppressed from that of the bare superconductor. Consequently, the superconducting transition temperature \( T_c \) and the heat diffusion properties of the TES device can be modulated by careful selection of the thickness of the layers. However, precisely achieving a target \( T_c \), is typically difficult, principally due to the process variations typically associated with conventional TES device manufacturing processes.

SUMMARY

Additional features and advantages of the disclosure will be set forth in the description which follows, and in part will be obvious from the description, or can be learned by practice of the herein disclosed principles. The features and advantages of the disclosure can be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the disclosure will become more fully apparent from the following description and appended claims, or can be learned by the practice of the principles set forth herein.

Disclosed are systems, methods, and non-transitory computer-readable storage media for forming sensors using transition edge sensors (TES) and their form are described. In one exemplary embodiment, a method includes forming a plurality of sensor arrays including at least one transition edge sensor (TES) device. The TES device includes a TES device body, a first superconducting lead extending over a first portion of the TES device body, and a second superconducting lead extending of a second portion of the TES device body, where the first and second superconducting leads are separated on the TES device body by a lead spacing, where the lead spacing is selected to be different for at least two of the plurality of sensor arrays. The method also includes determining a transition temperature for each of the plurality of sensor arrays and generating one or more signals responsive to detecting a change in the electrical characteristics of one of the plurality of sensor arrays meeting transition temperature criteria.

In another exemplary embodiment, a transition edge sensor (TES) is provided. The TES includes a substrate having an electrically insulating surface, a normal metal layer disposed on the electrically insulating surface, and a first superconducting lead disposed on a first portion of the normal metal layer. The TES also includes a second superconducting lead disposed on a second portion of the normal metal layer and separated on the normal metal from the first superconducting lead by a lead spacing, where the lead spacing is 20 times or less the normal metal coherence length for a target transition temperature.

In another exemplary embodiment, a computer-implemented method of designing a transition edge sensor (TES) sensor array is provided. The method causes a computing device to perform steps including defining a body for a TES device, the body includes a normal metal layer. The method also includes causing the computer device to define first and second superconducting leads for contacting the body, the first and the second leads separated by a lead spacing on the normal metal layer. The method further includes causing the
computer device to adjust at least the lead spacing to provide a transition temperature for the TES device meeting transition temperature criteria.

**BRIEF DESCRIPTION OF THE DRAWINGS**

In order to describe the manner in which the above-recited and other advantages and features of the disclosure can be obtained, a more particular description of the principles briefly described above will be rendered by reference to specific exemplary embodiments thereof which are illustrated in the appended drawings. Understanding that these drawings depict only exemplary embodiments of the disclosure and are not therefore to be considered to be limiting of its scope, the principles herein are described and explained with additional specificity and detail through the use of the accompanying drawings in which:

- FIGS. 1A-1D show a perspective view of TES device;
- FIG. 1E shows a plan-view of a TES device;
- FIG. 2 shows a log-log plot of measurements of effective $T_c$ for different currents as a function of lead spacing ($L$);
- FIG. 3 is a flowchart of steps in an exemplary method for designing a TES device in accordance with an exemplary embodiment of the invention;
- FIG. 4 is a flowchart of steps in an exemplary method for fabricating a sensor using a TES device in accordance with an exemplary embodiment of the invention;
- FIG. 5 is an exemplary configuration of a sensor, including a TES device designed in accordance with the various exemplary embodiments of the invention; and
- FIG. 6 is a schematic diagram of a computer system for executing a set of instructions that, when executed, can cause the computer system to perform one or more of the methodologies and procedures described herein.

**DETAILED DESCRIPTION**

Various exemplary embodiments of the disclosure are discussed in detail below. While specific implementations are discussed, it should be understood that this is done for illustrative purposes only. A person skilled in the relevant art will recognize that other components and configurations may be used without parting from the spirit and scope of the disclosure.

As described above, TES devices can be used as sensors across much of the electromagnetic spectrum. As such, TES-based sensors are useful in a variety of fields, including material analysis, mass spectroscopy of biomolecules, nuclear nonproliferation, synchrotron experiments, atomic physics, quantum information, dark-matter searches, and astrophysics, to name a few. However, to achieve high energy resolution for these applications, it is important to control both the $T_c$ and transition width ($\Delta T_c$) in a TES device. A transition width is generally used in lieu of transition edge to emphasize the fact that the transition is not instantaneous but rather requires a finite temperature range.

In general, since the energy resolution of calorimeters improves with decreasing temperature, many TES devices are typically designed to operate at temperatures around 0.1 K. For a TES, this requires a superconductor with $T_c$ in that range. While a few suitable elemental superconductors have a $T_c$ in this range, the best results have been achieved using proximity-coupled bilayers, as described above, in which $T_c$ is tuned by selection of the thicknesses of the superconducting (S) and normal metal (N) layers. However, as described above, a primary issue with TES-based detectors is that fabrication of TES devices is generally non-trivial with respect to obtaining a desired $T_c$. For example, process variation during the fabrication of TES devices can result in final layer thicknesses that deviate from target thicknesses. In most TES devices, even slight variations in layer thickness can significantly affect the resulting $T_c$ of a bilayer structure and render the TES device unusable for at least some types of particle detectors. In another example, it is generally difficult to produce a bilayer TES device in which the interface between the normal metal layer and the underlying superconductor layer is completely free of contaminants. Such contaminants have been found to introduce noise or alter the $T_c$ of bilayer TES devices. Chemical processes between the layers or interdiffusion of species at the interface can also cause problems in controlling $T_c$, $\Delta T_c$ uniformity and device behavior. Variation in intrinsic or extrinsic film stress is also known to cause changes in the resistive transition including $T_c$.

Efforts to improve the performance of TES devices have generally focused on reducing noise, improving absorption characteristics, and improving the interface or boundary between the normal metal layer and the underlying superconducting film. As a result, the parameters for adjusting $T_c$ in bilayer and other TES structures during fabrication are still generally limited to selection of types of materials, doping of materials, transmissivity of the interface, film stress, and thicknesses of layers. However, control of such parameters is generally difficult in most conventional TES device fabrication processes. As a result, fabrication yields for TES-based detectors are generally low.

Therefore, in order to overcome the limitations of conventional TES devices and fabrication thereof, the various exemplary embodiments of the invention provide a novel methodology for fabricating TES devices by providing an additional degree of freedom for selecting $T_c$. In particular, exemplary embodiments of the invention provide a design methodology in which the spacing between the superconducting leads of TES devices over the TES device body is selectively adjusted to further modulate $T_c$. Thus, lead spacing provides an additional degree of freedom for designing TES devices. Furthermore, since lateral spacing targets are typically easier to achieve in monolithic processes typically used for fabricating TES devices, this degree of freedom can be adjusted with a relatively high degree of accuracy. Thus, target $T_c$’s are significantly easier to achieve, improving yield of TES device manufacturing processes.

As used herein, the term “spacing” or “lead spacing,” with respect to the superconducting leads for a TES body refers to the average spacing of the portion of the superconducting leads contacting the device body of the TES device.

In general, a conventional bilayer structure or body in a TES device will have an intrinsic transition temperature $T_c$ prior to attaching any leads thereto. However, when superconducting leads are connected to opposite ends of the body, superconductivity is also induced longitudinally into the body from the ends via a longitudinal proximity effect. In the longitudinal proximity effect model the superconducting order parameter is a maximum in the TES near the leads then decays to a minimum halfway between the leads. Traditionally, it has been believed that in order to induce superconductivity longitudinally in a bilayer structure, the spacing between the superconducting leads needs to be less than two times of the mean free path length of a normal metal layer, typically on the order of the order of the film thickness when mean free path thickness limited and no larger than a few µm’s for bulk superconductor/normal metal/superconductor sandwiches with high purity normal metal. Further, the effect of such induced superconductivity has generally been a shift in...
Tc, on the order of 100's of mK, further complicating design of TES-based sensors when superconducting leads are used.

However, the present inventor has discovered that for at least some types of TES device structures, the longitudinal proximity effect still induces superconductivity even when the superconducting leads are separated by 100's of µm. Further, the present inventor has discovered that by providing superconductor lead spacing in the 100's of µm, the shift in Tc can be limited to 1 mK or less. Such mK Tc shifts can even occur for lead separations L of over 1000 times the electron mean free path in the TES body. In particular, as described below, the present inventor has discovered that the amount of Tc shift decreases predictably as 1/L2.

Accordingly, the various exemplary embodiments of the invention exploit this property to provide a new design methodology for TES devices. In particular, the various exemplary embodiments of the invention provide for design and fabrication of TES devices in which Tc can be selected by (1) varying the thickness of the layers in the body of the TES device and (2) varying the spacing of superconducting leads over the body of the TES device. Thus, the various exemplary embodiments of the invention allow a desired Tc to be targeted by selection of the thickness of layers in the body and the spacing of the superconducting leads to be used to tune the final Tc. This is conceptually described with respect to FIG. 1A.

FIG. 1A shows a perspective view of a TES device 100. As shown in FIG. 1A, the TES device 100 includes a substrate 101 having an electrically insulating surface and a body 102 on substrate 101. In FIG. 1A, the body 102 includes a superconducting layer 104 and a normal metal layer 106. The body 102 in FIG. 1A therefore forms a S/N structure having superconducting properties. In particular, normal metal electrons in 106 and superconducting order in 104 are diluted in the combined bilayer giving an intrinsic bilayer transition temperature Tc, In general, the bilayer structure will have a Tc value that is dependent on the thicknesses of layers 104 and 106, the conditions at the interface between the layers 104 and 106, and the Fermi metal properties of 104 and 106.

Although the body 102 in FIG. 1A is shown as including a specific bilayer structure, the invention is not limited in this regard. In other exemplary embodiments of the invention, the body can include a multi-layer structure. That is, a stack of alternating superconducting and normal metal layers on substrate 101. Further, the body 102 can also be formed by disposing the normal metal layer 106 on substrate 101 and thereafter forming the superconducting layer 104 on normal metal layer 106. Alternatively body 102 may be a uniform superconductor, a magnetically doped superconductor, a normal metal, a semiconductor or semimetal, or a magnetically doped metal.

Substrate 101 is a material which has lower conductivity than the body 102 so that it does not create a conducting path around the body 102. Further a material for substrate 101 can be selected which is not a source of impurities to the body 102. In one exemplary embodiment, the substrate is crystalline silicon substrate coated with a silicon nitride layer formed on its surface. However, the various exemplary embodiments of the invention are not limited in this regard and various other types of materials can be used to provide an electrically insulating surface for the body 102. The substrate can also be selected to be thermally conductive and can serve as a substrate to provide an absorber. Further, the substrate can be used to support additional circuits or devices coupled to the body 102.

Superconducting layer 104 and leads 108 and 110 can be made of any metal or metal alloy which is a superconductor at the operating temperature of the sensor. These superconducting layers can further be selected to be a metal that does not rapidly form a contaminant layer, such as an oxide, so that there are little or no impurities at their surfaces. A few elemental BCS superconductors include aluminum, molybdenum, titanium, and alloys including these metals. However, the invention is not limited in this regard and any other superconducting materials can be used in the various exemplary embodiments of the invention. Additionally, in some exemplary embodiments of the invention, superconducting layer 104 can be magnetically doped superconductors, for example, iron or manganese doped aluminum. However, the invention is not limited in this regard and other combinations of superconductors and magnetic impurities can be used in the various exemplary embodiments of the invention.

Normal metal layer 106 can be made of any metal or metal alloy which is a normal conductor at the operating temperature of the sensor. Layer 106 can be selected to be a normal metal that does not rapidly form a contaminant layer, such as an oxide, so that there are little or no impurities at its surface. Some normal metals include gold, silver, copper, palladium, platinum, gold/copper alloys, and palladium/gold alloys. An advantage of using metal alloys is their high sheet resistance, which is appropriate for some applications. The normal metal can also be a ferromagnetic material such as chromium, manganese, iron, cobalt and nickel, in which case the Tc of the bilayer can be suppressed well below the Tc of superconducting layer 104. In some cases, the normal metal can be a material such as tungsten which is a superconductor having a Tc below the operating temperature of the sensor, but is a normal conductor at the operating temperature. However, the invention is not limited in this regard and any other normal metals can be used in the various exemplary embodiments of the invention. In some exemplary embodiments of the invention, the normal metal layer can be other types of electrically conductive materials, such as semimetals or semiconductors. Thus, the term “normal metal,” as used herein, refers to any normal conducting materials can be used in the various exemplary embodiments of the invention. Normal metal layer 106 can be a magnetically doped metal, semimetal, or semiconductor.

In the structure illustrated in FIG. 1A, when superconducting leads 108,110 are disposed on the body 102, these superconducting leads also induce a superconducting order in 102. As a result, the TES device is effectively a SNS structure and the Tc of the TES device is increased above the transition temperature of body 102 in isolation. Tc becomes dependent on the Tc of the superconducting leads 108 and 110. However, since the order parameter is changing longitudinally in the TES and there is a region of minimum order parameter strength in 102 (in the particular TES designed in FIG. 1A, the minimum is along the line bisecting L halfway between the leads). That is, the path between leads 108 and 110 through layer 102 operates as a superconducting weak link. It follows that the resistive transition and the devices Tc is inherently current dependent and increasingly so as L is decreased. Further, as described above, the effect is strongly dependent on the spacing (L) between the leads 108 and 110. Thus, as the leads 108 and 110 are brought closer together (i.e., L is reduced), the strength of the order parameter at the minimum along the line bisecting L increases therefore increasing the devices Tc, for a given current. Conversely, as the leads 108 and 110 are separated (i.e., L is increased), the strength of the order parameter at the minimum along the line bisecting L decreases therefore decreases.
ing the devices \( T_e \) for a given current. Therefore, as the amount of superconducting order induced varies, the shift in \( T_e \) will also vary. This shift in \( T_e \), as a function of spacing is shown below in FIG. 2.

It is worth noting that the temperature at which the penetration of order into 102 is zero (i.e., no superconducting order induced) requires going above the \( T_e \) of the superconducting material for lead 108 and 110. This temperature is typically much higher than the device operating temperature (e.g., lead \( T_e \) is often of the order of several Kelvin as compared to a 100 mK \( T_e \) device). As a result, this produces at temperatures higher than the sharp resistive transition a gradual decrease in resistance as the temperature is lowered corresponding to a small leakage of superconducting from 108 and 110 into 102. Therefore, in some exemplary embodiments of the invention, this property of the longitudinal proximity effect on the normal state slope can be used as a design feature in TESs to provide extended spectra range of suboptimal energy resolution. That is, the detector can then be designed to give the best energy resolution in a specified particle energy window. Thus, this feature is operative to prevent heat pulses from saturating the TES device for parallel inverse proximity effect is induced countering the separation distance \( S \) between features 114 and 116. This is shown in FIG. 1D, rather than forming leads 108 and 110 overlapping body 102. Thus, a portion of leads 108 and 110 contacts the sidewall portions of body 102. However, for purposes of adjusting \( T_e \), the spacing of interest is still the same as in FIG. 1A, the spacing between the leads on the top of body 102, as shown in FIG. 1B.

In another configuration, as shown in device 140 in FIG. 1C, the leads are formed on at least a portion of the sidewalls of body 102. In such a configuration, the spacing of interest is then the length of the body 102. In yet another configuration, as shown in device 150 in FIG. 1D, rather than forming leads 108 and 110 separately from superconducting layer 104, they are formed concurrently. In particular, once superconducting layer 104 is formed, normal metal layer 106 is formed over only a portion of a superconducting layer 104. As a result, the portions of superconducting layer 104 having no normal metal material disposed thereon form the leads 108 and 110, as shown in FIG. 1D. In such a configuration, the body is defined by the normal metal layer and the directly underlying portion of superconducting layer 104. As a result, similar to device 140 in FIG. 1C, the spacing of interest is the length of the normal metal layer 106.

As described above, in addition to providing a spacing for \( L \) to adjust \( T_e \), \( T_e \) can also be adjusted by selection of materials, layer thicknesses, and incorporation of magnetic impurities. However, in some exemplary embodiments of the invention, in addition to adjustment of the lead spacing, normal metal features can be disposed on a S/N bilayer (i.e., superconducting/normal metal/substrate) between the leads. This is shown in FIG. 1E. FIG. 1E is a plan-view schematic of a TES device 150 in accordance with some exemplary embodiments of the invention. As shown in FIG. 1E, between the leads 108 and 110, normal metal features 114 and 116 are formed on the top of body 102. In the various exemplary embodiments of the invention, the shape of such features can vary. Further, any combination of geometric shapes can be used in the various exemplary embodiments of the invention for features 114 and 116.

Typically, such features are provided to reduce excess electrical noise in the devices and give detectors an improved energy resolution. However, the present inventor has found that for at least some types of TES device structures, these additional normal metal features can also be used, in conjunction with the spacing \( L \), to provide further adjustment of \( T_e \) in areas far from leads 114 and 116. In particular, by changing the separation distance \( S \) between features 114 and 116, a lateral inverse proximity effect is induced countering the effect of \( L \). The size of the reduction in \( T_e \) is found to scale as \( -1/S^2 \). Thus, in exemplary embodiments of the invention including such features, adjustment of both \( L \) and \( S \) can be used to adjust the effective \( T_e \) of the TES device.

As described above, the relationship between the change in \( T_e \) and spacing \( L \) is related by \( \Delta T_e \sim -1/L^2 \). This is shown in FIG. 2. FIG. 2 shows a log-log plot of measurements of effective \( T_e \) for different currents as a function of lead spacing \( (L) \). The fabricated TES devices were measured using currents of 10 nA, 100 nA, 1 uA, 10 uA, and 100 uA. The data for FIG. 2 was collected by measurements of TES devices having a body including a bilayer of 55 nm molybdenum (Mo) and 21.0 nm of gold (Au), where \( T_e \) for Mo —0.9K and \( T_e \) for the body is —170.9K. The TES devices further include superconducting leads fabricated from a molybdenum/niobium (Mo/ Nb) alloy, having a \( T_e \) ranging from 3.5—7.1K, with a lead spacing \( (L) \) ranging from 8 to 290 um.

As shown in FIG. 2, the measurements exhibit two characteristics. First, FIG. 2 shows that as electrical current is increased, the overall variation in \( T_e \), is reduced. For example, the data points associated with 100 uA current show that \( T_e \) goes from about 169.5 mK at a 290 um spacing to 240 mK at an 8 um spacing. In contrast, the measurements associated with 10 nA current show that \( T_e \) goes from a little over 171 mK at a 290 um spacing to over 500 mK at an 8 um spacing. Second, FIG. 2 shows that as lead spacing varies, the \( T_e \) of the TES device varies approximately as \( 1/L^2 \). Since \( T_e \) of the body is relatively weakly current dependent (—171 the observed variation in \( T_e \) reflects the change induced in the \( T_e \) of the TES device provided by the superconductivity induced by the Mo/Nb leads. Thus, by adjusting the lead spacing from 8 um to 290 um, the \( T_e \) of the body can be adjusted as much as ~100’s of mK and to less than ~1 mK. Although, the lead spacing can be increased beyond 100’s of microns, this results in shifts of less than 1 mK.

Accordingly, since the relationship between lead spacing and \( T_e \) is predictable and the range of spacing over which the longitudinal proximity effect is operative induces changes in \( T_e \) of 100 mK or less, such adjustment of lead spacing can be used during design and fabrication of high-resolution TES devices with target \( T_e \)'s in the 100’s of mK. Such a design methodology is illustrated in FIG. 3.

FIG. 3 is a flowchart of steps in an exemplary method 300 for designing a TES device in accordance with an exemplary embodiment of the invention. Although only a limited num-