GERMANIUM INFRARED POINT SOURCES

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INTRODUCTION

It has been previously reported that if an electric current is brought through a pin point in a semiconductor material such as germanium, the electrons are attracted towards the point, thereby leaving holes in the semiconductor material. The recombination of electrons from the negative electrode with these holes causes the emission of infrared radiation at about 1.8 to 3 microns.[13] This phenomenon is evident in most semiconductors under the same conditions; i.e., the injection of positive holes in a semiconductor of the M-type or the injection of electrons in a semiconductor of the P-type will cause this effect.

It has also been previously reported that germanium is transparent to infrared radiations beyond 1.8 microns, but its transparency can be modulated by an electric current.[15] The modulated transparency of the semiconductor material is probably caused by the formation of holes, as described in the paragraph above.

Germanium infrared point sources[14] have been developed that utilize the above described phenomena in devices for the modulation, transmission and reception of infrared radiant energy and for the establishment of radiation barriers for the scanning of an area to sense the presence of objects. The ease of modulation of these sources coupled with their efficient infrared output allows their use in devices for transmitting and receiving infrared radiation over relatively long distances. Because of the very low time constants of the sources and detectors, the devices will perform even more satisfactorily than normal telephonic communication equipment.

The narrowness of the infrared energy beam emitted from the source makes it preferable to transmit the signals between two fixed points or to utilize special supplementary

equipment for aiming the transmitter at the receiver, or vice versa. This paper will review the historical and theoretical aspects of the phenomenon and discuss methods of utilizing improved germanium infrared point sources in communication devices.

HISTORICAL

Loesew [1,2] first observed the injected light emission from crystals of silicon carbide in 1924. The early literature [3,4] related the light emission to the presence of an "active layer" on the surface of the crystal. Later the light emission was attributed to the Bremstrahlung of electrons. [5,6] This theory did not explain the fact that spectral distribution was nearly independent of the applied field strength.

Two types of emission were reported (a) a bluish light, and (b) a yellow light, the type emitted depending on the direction of current flow. The parts of the crystal emitting the yellow light did not coincide, in general, with those emitting blue light or current reversals; nor did the same crystal necessarily emit both types. It was concluded, therefore, that the mechanism of exitation differed for the two cases.

To disprove the "active layer" theory of light emission, [3,4] Lossow removed the layer by grinding and measured the resistance between two probes placed on the surface at various intermediate stages of the grinding process. [7] The resistance was found to increase by several orders of magnitude with progressive removal of material and then to drop sharply after twelve microns had been removed. Probing the potential distribution while current was passing from the surface to the crystal showed the presence of a rectifying junction at the boundary of the active layer and the bulk silicon carbide. Yellow light emission occurred when the current passed through the boundary in the forward direction. In a later paper it was mentioned that the active layer consisted of an n-type layer, whereas the bulk consisted of p-type material.

Tetzner investigated the luminescence phenomena observed during the passage of currents through impure silicon carbide crystals.[8] He noted that their appearance depended on the polarity of the applied voltages. When silicon carbide was the cathode, luminescence occurred over a small area surrounding the metal electrode and appeared to be located just below the glassy surface. Probe measurements showed this region to be well-conducting. When the crystal was made the anode, blue or green luminescence appeared in the form of irregularly distributed pinheads. Anodic luminescence required higher voltages. Tetzner also investigated the use of electrolytes as an alternative to metal electrodes.

It was considered that the mechanism of cathodic luminescence was similar to that of normal phosphors except that the luminescence centers were replaced by larger "luminescent domains". The process was thus expected to depend on impurity content since its absence in chemically pure silicon carbide had been confirmed. Both forms of emission had very short decay periods.

When a crystal was irradiated with ultra violet light, the areas which fluoresced coincided with the regions of cathodic luminescence. The regions of anodic luminescence could not be similarly excited. Anodic luminescence was thought to be a thermal effect due to highly localized power dissipation in internal spreading resistances.

In 1951 Lehovec, et al investigated the injected light emission of silicon carbide crystals.[9] Previously published data on the intensity and spectral distribution of the light had been of a qualitative nature. Lehovec, et al investigated the emission as a function of temperature and of current through the crystal. They found that the emission spectrum extended from 4500Å to 6500Å at room temperature and was nearly independent of current from 0.1 ma. to 50 ma. The

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light intensity increased approximately proportionally to current (efficiency about 10^6 quanta per electron at room temperature for a particular crystal.) (See Appendix for a discussion of the experiments).

New photoelectric devices utilizing carrier injection were disclosed by Lehovec in late 1952.[10] The detection of injected carriers by their absorption and by emission due to their recombination with majority carriers was discussed. Two new components were proposed, (1) The "photo modulator" which permitted modulation of a light beam by the change in absorption due to injection carriers, and (2) the "graded seal junction" which permitted light to be transmitted to and from a p-n junction without substantial absorption in the bulk semiconductor.

In 1953 Lehovec published a paper on the light emission produced by current injected into a green silicon carbide crystal.[11] He discussed the light emission which arises from the passage of a current in the forward direction over a p-n barrier in a transparent (pure) silicon carbide crystal. The results differed from previous results obtained on a dark blue ("impure") silicon carbide crystal in several respects. The spectral distribution of light emission was found to be independent of current and temperature. Both the efficiency of light emission and the decay constant of light emission increased exponentially with decreasing temperatures. This was explained by a non-radiative transition of excited electrons. In a dark blue silicon carbide crystal the resistances in s eries with the p-n barrier were largely eliminated, and light emission at a voltage of the same magnitude as hv/e, was observed.

Newman reported on his optical studies of injected carriers in 1953.[12] He investigated the radiation produced by the direct recombination of electrons and holes in germanium.

Briggs and Haynes[13] received a patent on methods and devices for generating infrared energy. This was accomplished by creating a high rate of recombination of electron-hole pairs in semiconductors by injecting foreign charge carriers into the semiconductor body. (See discussion in Appendix).

INFRARED POINT SOURCES AND THEIR APPLICATION
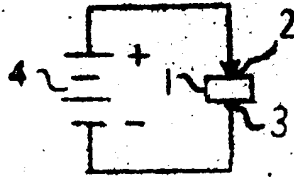
Fig.1 - ARRANGEMENT FOR PRODUCTION OF INFRARED ENERGY FROM A PIECE OF SEMICONDUCTOR MATERIAL

The Briggs and Haynes infrared emitting device,[13] Figure 1, comprised a single crystal of n-type germanium 1, a point contact to the germanium 2, a base 3, all connected in series with a dc current source 4. The positive point contact electrode caused a migration of electrons in the germanium towards the positive electrode 2 with a consequent formation of holes in the germanium 1. Electrons from the negative electrode 3 then entered the germanium and combined with the holes. This combination of electrons with the holes occurred with an emission of infrared energy at approximately 1.8 to 3 microns.
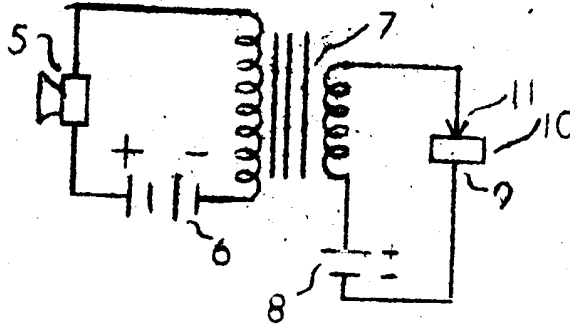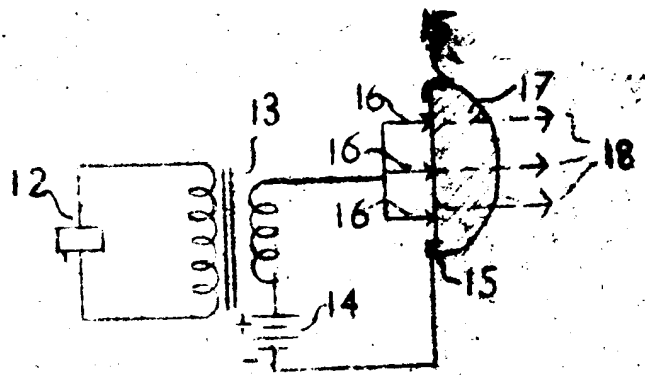
**Fig.2 — MODULATING DEVICE FOR SINGLE POINT CONTACT SEMI-
CONDUCTOR SOURCE.**

     Modulating the infrared energy emitted from the
germanium source was accomplished as shown in Fig.2.
Speaking into the microphone 5 caused a fluctuation of
current from the dc source 6 to pass through the primary
coil of the transofrmer 7. The secondary coil of the
transformer 7 then modulated the output of the dc source 8
and the current flowing from the base 9 into the germanium
pellet 10 modulated the electron flow to point contact 11,
thus causing a modulated infrared emission from the germanium
pellet. It was important that the polarity of the device be
sufficient so that the direction of electron flow within the
germanium 10 did not change. It was possible by this method
to modulate the infrared output up to very high frequencies
(in the order of megacycles per second).

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The radiation emitted from the germanium pellet was observed to be only in the infrared region. Because there was no emission of visible light, an infrared filter was not necessary as in the usual infrared projection devices. The germanium, being transparent to the infrared radiation formed by the recombination of holes and electrons, permitted the escape of the radiation for projection purposes.

Recently semiconductor infrared sources have been constructed in such a manner so that they have an optimum geometric shape determined by the general principles of optics for the projection of fine beams of infrared radiation. The exit surface of the semiconductor has been shaped to constitute a diopter approximately stigmatic in relation to the point of emission to provide for optimum focusing. The infrared radiation was emitted very close to the point contact but the combination of the point contact and the stigmatic diopter shape of the germanium crystal furnished an apparent pin point source which, when placed at the focus of an optical instrument such as a mirror, yielded very fine beams of radiation without appreciable aperture. For some applications, however, it was advantageous to form the germanium pellet so that the emitted radiation was not focused.

The optimum operating current for the above described units was up to 500 milliamperes at 0.5 to 1.0 volts.

Fig.3 - MODULATING DEVICE FOR MULTIPLE POINT CONTACT SEMI-CONDUCTOR IR SOURCE

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The germanium crystal 17 in Fig.3 above, was employed
as an infrared emitter utilizing several point contacts 16 for
the positive electrodes. Several points were used instead of a
single point to increase the infrared radiation output of the
germanium crystal. The points were placed close together so
that the geometric form of the germanium crystal could focus the
radiation emitted from all the points. An oscillator 12 emitted
a signal which passed through transformer 13 and modulated the
current input from the dc source 14. Electrons within the
germanium migrated towards the positive point electrodes 16 and
new electrons entered the germanium crystal through the negative
electrodes 15. The combination of the electrons entering the
crystal through 15 with the holes produced by the migration of
electrons already in the crystal towards points 16 produced the
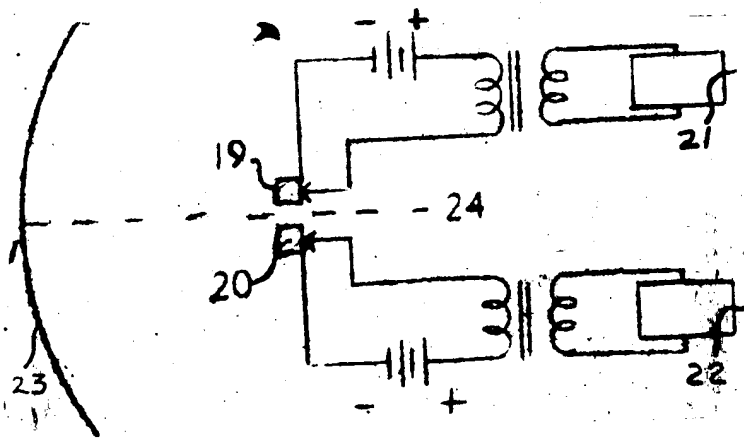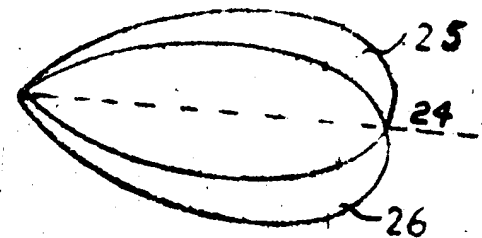infrared energy which was emitted as shown by dotted lines 18.

Fig. 4   Fig. 5

DEVICE FOR PRODUCING A FINE NON-MODULATED BEAM OF INFRARED
ENERGY BETWEEN TWO AREAS OF MODULATED INFRARED ENERGY.

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In Figure 4 two germanium pellets 19 and 20 were placed at the focal point of a mirror 23. A signal of 400 cycles per second was emitted by the oscillator 21, thus modulating the current entering the germanium crystal 19. Another oscillator 22 emitted a signal of 1,000 cycles per second, thus modulating the current into the crystal 20. The modulated infrared energy output of the crystals 19 and 20 impinged on mirror 23. Two modulated infrared beams were reflected, one at 400 and the other at 1,000 cycles per second. The intersection of these two beams comprised a narrow beam 24 which was sensed as a non-modulated continuous signal.

Figure 5 shows diagrammatically the areas covered by the infrared energy reflected by mirror 23 in Figure 4. Area 25 represents the 400 cycle beam. Area 26 represents the 1,000 cycle beam. The continuous non-modulated beam is shown by line 24.

It was thus possible by the use of the device represented by Figure 4 to provide an extremely fine beam of infrared energy that can be used for the alighment of signal devices.
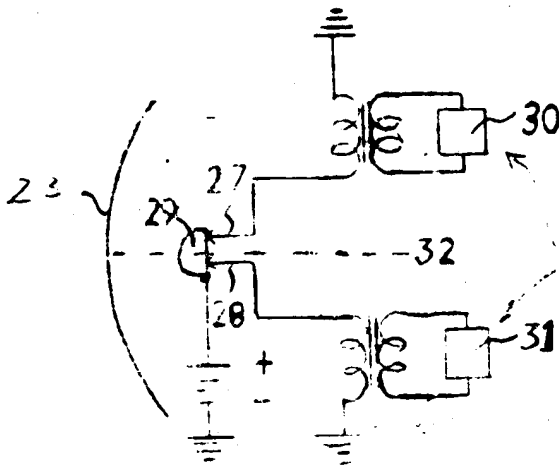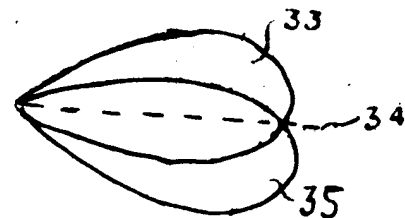

Fig.6

Fig.7

DEVICE FOR PRODUCING A FINE BEAM OF NON-MODULATED INFRARED
ENERGY BETWEEN TWO AREAS OF MODULATED INFRARED ENERGY EMPLOYING
A SINGLE SEMICONDUCTOR UNIT.

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In the figure above a single crystal of germanium 29 was placed at the focal point of the mirror 23 instead of the two crystals of germanium used in the apparatus shown in Figure 4. The oscillator 30 emitted a signal of 400 cycles per second through point 27 into the germanium 29. The oscillator 31 emitted a signal of 1,000 cycles per second through the point 28 into the germanium 29. The modulated infrared energy emitted from the points 27 and 28 impinged on mirror 23 and was reflected in the pattern shown in Figure 7. The device represented by Figure 6 could also be operated in another manner. The output of oscillators 30 and 31 could be modulated at the same frequency, for example, 400 cycles per second. The output of oscillator 30, however, would be modulated so that the signal would be transmitted as short pulses, or dots. The output of oscillator 31 would be modulated in such a manner so that the signal would be transmitted as long pulses, or dashes.

In Figure 7 area 33 represents the infrared energy emitted from crystal 29 at point 27 which has been reflected by the mirror 23. Area 35 represents the infrared energy emitted by crystal 29 from point 28 and reflected by mirror 23.

In the case where two different frequencies were produced, a detector placed in area 33 received a modulated signal of 400 cycles per second. The detector in area 35 received a 1,000 cycles per second signal, and the detector in the area represented by line 34 received a continuous signal. In the case where the output of each oscillator was the same but the signal was emitted in dots and dashes, a detector placed at area 33 would receive dots at 400 cycles per second. A detector placed in area 35 would receive dashes at 400 cycles per second, but the detector placed in the area represented by line 34 would receive a continuous signal.
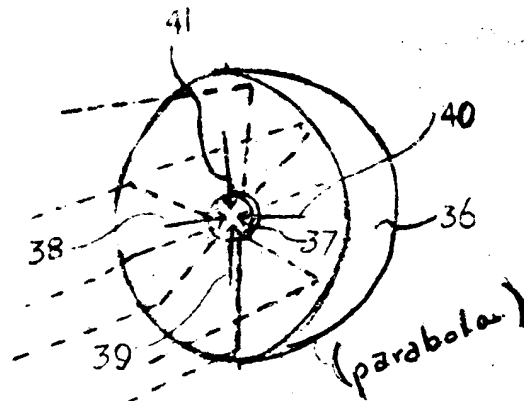
Fig. 8 – RADIATION PATTERN PROJECTED BY SEMICONDUCTOR IR SOURCE WITH FOUR POINT CONTACTS

In figure 8 a germanium crystal 37 was placed at the focal point of the parabolic mirror 36. The crystal had four infrared emitter points, 38, 39, 40 and 41. By employing the procedures described in this report, the output of each point could be modulated at a different frequency or at the same frequency but with different pulse durations. For example, the output at points 39 and 41 could be 400 cycles per second with one point emitting dots and the other dashes. The output of points 38 and 40 could be kodulated at 2,000 cycles per second with one point emitting dots and the other dashes. At the receiving station a high frequency signal (2,000 c.p.s.) and a low frequency signal (400 c.p.s.) could be detected around an axis which is a straight line in space at approximately the axis of the parabolic mirror 36. The signal reflected at the axis of the mirror would be received as a continuous signal by a photosensitive cell.
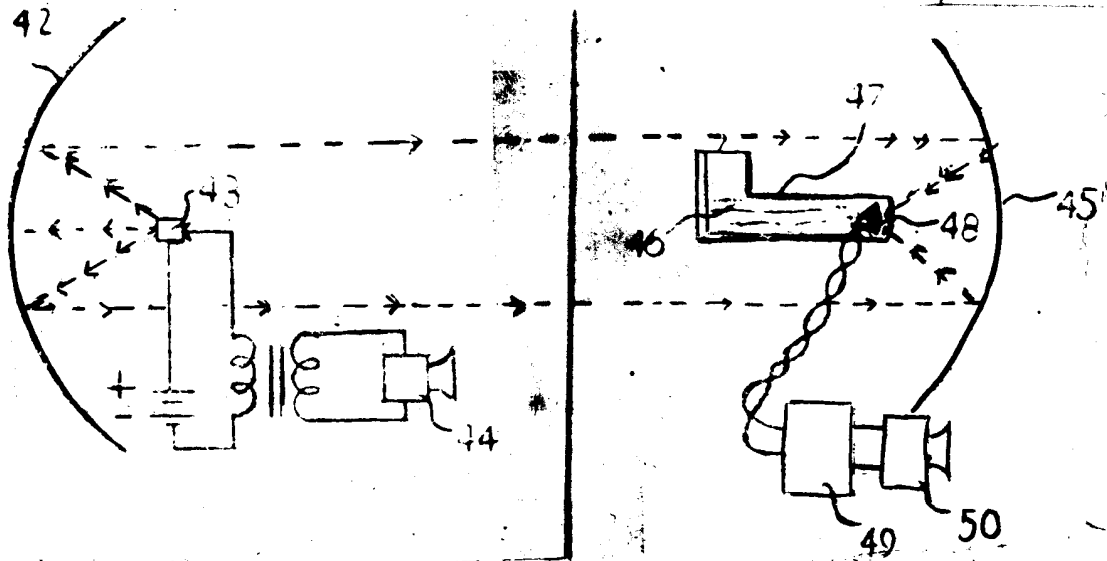
Fig. 9 — COMMUNICATION SYSTEM EMPLOYING IR POINT SOURCE

In Figure 9 the infrared output of germanium source 43 was modulated by microphone 44. The emitted infrared radiation impinged on mirror 42 and was reflected on to mirror 45, then to the photoconductive surface 48 of photocell 47. The resistance of the photoconductive surface 48 changed with the variations in impinging infrared radiation and the modulated output of the cell was amplified by amplifier 49. The electrical output of amplifier 49 was then received by speaker 50.

The germanium 43 has an infrared emission spectrum with a peak at 2.5 microns. There is no visible light emitted. Lead sulfide cells are sensitive up to 3.5 microns at room temperature and up to 4 microns at the temperature of liquid air (-180°C). Lead telluride cells are sensitive to 6 microns when cooled to the temperature of liquid air (-180°C). Either cell can be used in the device represented by Figure 9 or in any of the devices described in this report employing infrared responsive photoconductive cells.

It is important to note that the efficiency of the device represented by Figure 9 is high because no infrared filter or lenses are necessary for the transmission or reception of the infrared radiation. In devices previously reported, an incandescent infrared source such as a tungsten filament lamp was employed. Filters had to be used in these devices so that only the infrared energy would be transmitted. A germanium source, optically shaped, will project a beam without the filter or lenses necessary in other types of infrared projection apparatus.
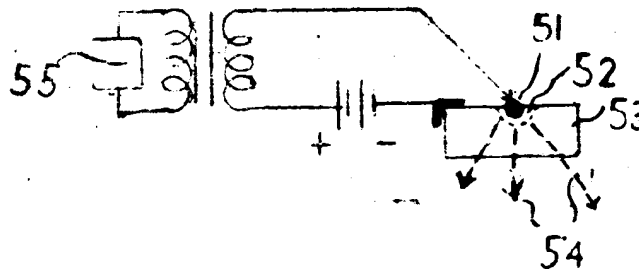
Fig.10 - Indium UNDER GE POINT CONTACT

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It has been previously reported that the deposition
of indium in pellet or layer form on an n-type germanium crystal
directly under the point electrode contact will increase the
hole density in the area adjoining said contact.   In Figure 10
an n-type germanium crystal 53 is employed as an infrared
emitter.   An indium pellet 51 is placed in or on the surface of
the crystal directly under the point contact electrode by
mechanical means or by electrodeposition.   A modulated signal
from oscillator 55 causes the metal at 51 to become more positive,
attracting electrons from the germanium.   This will increase the
hole population throughout the germanium, but particularly in area
52.   In effect, then area 52 becomes a p-type germanium section.
The inclusion of the pellet or layer of indium or other metal with
similar properties under the point contact is advantageous because
the infrared output of the crystal is increased, the units are
easier to manufacture, and the resulting impedance values of the
device are more satisfactory than that of pure germanium for in-
strumentation purposes.
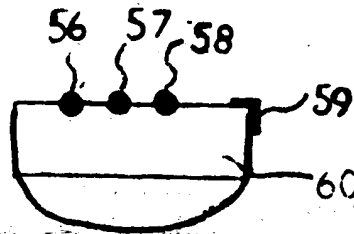
Fig.11 - IR POINT SOURCE EMPLOYING 3 INDIUM PELLETS

Multiple electrode structures on a single germanium
crystal blank have also been produced. (Figure 11). Indium
pellets 56, 57 and 58 were set into the hemisphere of the n-
type germanium crystal 60 directly under the positive point
contact electrodes and the negative electrode 59 was positioned
on the side of the hemisphere.   The pellets were placed
sufficiently close to the center of the shaped crystal so that

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the infrared radiation was emitted approximately normal to the
crystal surface.   The infrared source, composed of the indium
or similar metal between the point contact and the semiconductor
material was employed in some of the devices described in this
report.
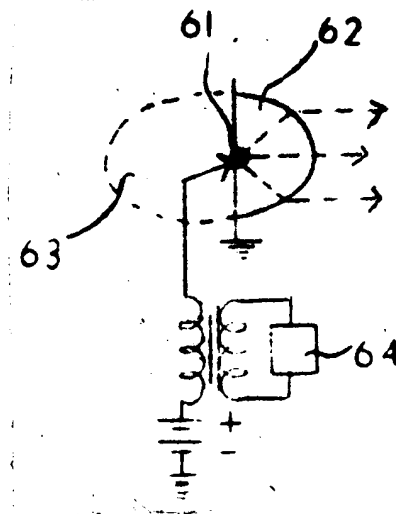
Fig. 12 - IR POINT SOURCE - CARTESIAN OVAL

It may be assumed that the emission area in the
germanium source is almost a pin point.   It is then possible
to determine the best procedure for projection of the infrared
energy in a narrow or broad beam.   One method would be to use
a hemisphere shaped germanium source in combination with a
mirror which would gather and reflect the infrared energy with-
in a wide angle.   The infrared radiation emitted from the
germanium source, could also be focused by a proper shaping of
the germanium crystal.   For example, if emission takes place
at 61 in Figure 12, the portion of the germanium which allows
the exit of a parallel beam from point 61 is a section 62 of
the Cartesian oval 63.   With the Cartesian oval section it is

not necessary to use a mirror or lens to project a narrow
parallel beam of infrared energy from the crystal.
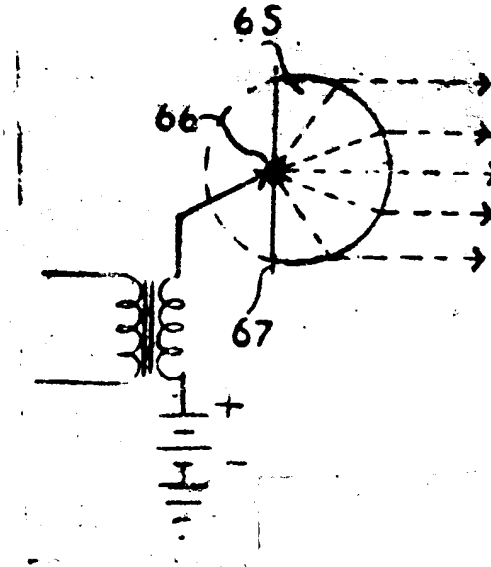
Fig.13 - IR POINT SOURCE - SPHERE SECTION

The index of refraction of germanium in the infrared
region is approximately four.   Calculations indicate that
with an index of refraction of four, the Cartesian oval des-
cribed above is almost a sphere.   Thus the practical solution
in the production of the infrared source was to use a cross-
section 65 (Figure 13) of a germanium sphere cut slightly
beyond its center at 67.   The point electrode was placed at
66.   The plane at which the sphere of germanium was cut to
get the desired focus of emitted infrared energy was determined
mathmatically or by infrared measurements on the emission from
the sphere as it was being shaped to conform with the optimum
geometric configuration for projection of parallel beams of
infrared radiation.
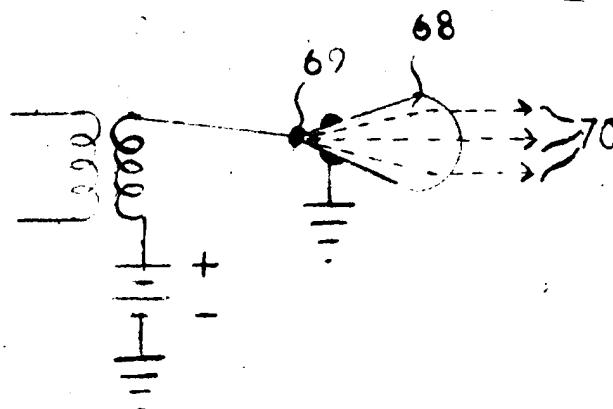
Fig. 14 - IR POINT SOURCE-CONICAL CROSS SECTION OF A CARTESIAN OVAL

Figure 14 shows the use of a conical cross-section 68 of a Cartesian oval. The point contact 69 with an indium or similar metal underlay is at the apex of the cone, permitting the emission of parallel beams of infrared energy as represented by dotted lines 70. This shape allows optimum utilization of the germanium with a minimum amount of material. The impedance of the unit is also higher than in the germanium hemisphere, because of the conical shape of the source. The device will project parallel beams of infrared radiation quite satisfactorily, even though there may be some loss of lateral radiation at the point contact.
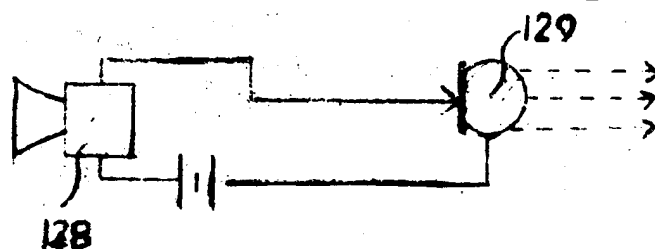
Fig.15 - MODULATION OF IR POINT SOURCE

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The germanium infrared source requires a current
of about 600 to 800 milliamperes per point for satisfactory
operation. When an indium layer or pellet is placed between
the point and the germanium, the current requirements are
substantially higher. The germanium source thus requires a
dc power supply of the same order of magnitude as that required
for the operation of a standard carbon microphone. Figure 15
shows an arrangement whereby the modulation of current from
the direct current source by the carbon microphone 128 will
produce a modulated infrared signal from the germanium source
129. It is thus possible to construct a very simple germanium
infrared source for short distance communication without
complex electronic, optical or mechanical systems.

A P P E N D I X

U.S.Patent 2,683,794 – INFRARED SOURCES
Howard R.Briggs and James R.Haynes
Assigned to Bell Telephone Laboratories
Patented July 13, 1954.

The invention discloses devices and methods for
generating infrared energy with semiconductor point source
devices. The radiation can be generated in narrow frequency
band widths and in controlled intensities. The infrared
energy is generated by recombination of electron-hole pairs
in the semiconductor.

Only extrensic semi-conductors are considered in
the invention. An extrensic semiconductor has the
characteristic that the conductivity at room temperature is
largely due to the presence of impurity atoms. If these are
of a type which furnish excess electrons, the impurity atoms
are called donors and the semiconductor is known as n-type.
Conversely, if the impurity atoms provide electron deficits
or holes, the atoms are called acceptors and the semiconductor
is known as p-type. If both acceptor and donor impurities
are present, the semiconductor will be either n or p type
depending upon the excess of the one impurity over the other
and the conductivity so produced is due either to excess
electrons or holes, but not both. The concentration of
excess electrons or holes due to impurities is a constant at
any given temperature, depending only on the composition of
the semiconductor.

This invention requires the presence of both free
electrons and free holes simultaneously in the material so
that direct electron-hole recombination will occur to produce
radiation. High concentrations of free electrons and free
holes are necessary for the production of radiation and, there-
fore, it is advantageous to use material having an excess

concentration of either donor or acceptor atoms so that the
concentration of either holes or excess electrons is high
prior to the injection of charge carriers of the opposite type
into the material.

Silicon and germanium are described as preferred
materials for the infrared generator in accordance with the
invention.

The crystalline form of both germanium and silicon
is the diamond lattice in which each atom forms four covalent
(electron pair) bonds with neighbouring atoms. The electrons
in these covalent bonds are unable to move in electric fields
of ordinary intensity and thus do not contribute to the
electrical conductivity of the crystal. It was found however
that if visible light was allowed to fall on the germanium or
silicon crystal, some of the valence electrons are ejected from
the bonds leaving behind electron deficits, or positive holes.
Both the ejected electrons and holes are capable of moving in
an electric field so that the conductivity is increased.

As the wavelength of the light used to irradiate the
crystal is continuously increased, the incident quanta have
progressively less energy. A point is finally reached at
which the incident quanta have just sufficient energy to break
a covalent bond and so produce an electron-hole pair. The
corresponding wavelength is known as the internal longwave
limit of crystal. Careful measurements of the increase in
conductivity and incident light intensity showed that one
electron-hole pair was produced for each photon of light
absorbed for light with quanta having sufficient energy. The
minimum energy required to produce an electron-hole pair and
thereby increase the number of free charge carriers was that
which would transfer an electron having maximum energy in the
valence band to a condition of minimum energy in the conduction
band. This minimum energy was found to be 1.1 ev. for silicon
and 0.7 ev. for germanium. Thus, the internal longwave limits

for these materials are about 1.2 and 1.8 microns respectively.

The conductivity which is an index of the number of free charge carriers present can be increased in a semiconductor by the application of forms of external energy other than light energy. The increase in the conductivity of intrinsic semiconductors with temperature is usually due to the breaking of large numbers of valence bonds by thermal energy.

The conductivity of semiconductors can also be increased by carrier injections. This may be done by causing a current to flow from a metal point into an n-type semiconductor or from a p-type semiconductor into a metal point. Large concentrations of injected carriers can also be obtained by using a p-n junction with current flowing from the p to the n-type material so that electrons are injected into the p-type semiconductor and holes into the n-type. Since neutralization of space charges requires that each minority carrier be accompanied by an additional carrier of the opposite side, extremely high densities of excess electrons and holes can be produced in the immediate vicinity of the junction. whenever the conductivity of the semiconductor is increased by one of the above means. The crystal reverts to its original conductivity when the energy source is removed. Thus, if the voltage applied across the p-n junction is suddenly removed, the carrier concentration in the neighbourhood of the junction decays to its original value. This restoration of the original conductivity implies some process or processes of recombination of the injected charge carriers and carriers of the opposite sign present in the material.

The Conservation of Energy Law demands that the recombination of an electronhole pair be accompanied by the release of an amount of energy equal to that required to produce a pair. Conceivably this energy may appear either in the form of quanta of thermal lattice vibrations (phonons), or

it may be radiated in the form of light quanta (photons),
or both.   With carrier concentrations ordinarily obtained
in semiconductor devices of the prior art, only an extremely
small fraction of recombination energy could have been of a
nature which would appear as characteristic radiation. Only
with extremely high concentrations of free carriers can the
chance of direct electron-hole capture be made at all
comparable to that of carrier capture through recombination
centers so that usable amounts of characteristic radiation
result.   Electron-hole concentration rates sufficient to
produce usable quantities of substantially single frequency
electromagnetic energy can be obtained by injecting charge
carriers of one type at high rates into properly prepared
and shaped bodies of semiconductor material which normally
contain an excess of charge carriers of the opposite type.
Thus electrons can be injected into p-type material, holes
can be injected into n-type material or an n-p junction can
be utilized by drawing a forward current across it to inject
electrons from the n-section into the p-section and holes
from the p section into the n section.

The narrow range of radiation frequencies associated
with the energy evolved in the dropping of an electron across
the entire forbidden band of the material is referred to as
characteristic radiation as opposed to that form of radiation
having a broad emission spectrum called black body radiation,
resulting from thermal agitation at high temperature.

Various means of injecting charge carriers to a
semiconductor are known and may be employed to generate
characteristic infrared energy.   For example, by the applica-
tion of visible light to a semiconductor, or by bombardment
of the semiconductor with high energy particles. In the
following discussion, the term injection is intended to in-
clude excitation of minority charge carriers by incident

light or bombardment as well as emission of carriers from
physical contact.   Minority charge carrier injection
rates equivalent to that obtained from an emitter at a
current density of at least 10 amp. per square centimeter
is sufficient to produce usable infrared energy.

A crystal of germanium or silicon, having
significant impurity in its various portions, so that these
portions are highly conductive, (i.e. of the order of 0.01
to 0.1 ohm^{-1}cm^{-1}) is provided with one portion which is of
strongly n-type material and another portion which is of
strongly p-type material.   Such an n-p junction can be
employed as an excellent emitter of foreign carriers into
both the n and p type portions of the semiconductor body
biased by a current in the forward direction of conduction,
i.e. where the p-type material is biased positive relative
to the n-type material.   The resulting recombination
produces energy at least a portion of which is infrared
radiant energy of a narrow band width.   By changing the
intensity of current at the n-p junction, the infrared out-
put is changed, thus an on-off signal, or a signal of
modulated intensity is produced.

From the theory of electro-magnetic wave generation
set forth above it is to be expected that the characteristic
recombination in a semiconductor would occur across a fixed
energy gap and a sharp and definite wavelength of energy
would result.   The wavelengths of the energy obtained from
characteristic recombination in actual semiconductor samples,
extend over a range which may be as wide as a few tenths of
a micron.   This apparent anomaly resulting from a lack of
sharp characteristic wavelengths may be partly due to kinetic
energy at the holes and electrons, and partly to variations
in the energy gap of the material actually produced by

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thermal vibration of the crystal lattice. It has been
observed that the radiation intensity does not have the
broad wavelength distribution characteristic of a black body,
but is sharply peaked. The peak value is quite close to
the best estimates of the energy required to break a covalent
bond and so produce an electron-hole pair in germanium.

It was found that the radiation intensity increased
as the sample was cooled so that about five times as many
quanta were radiated at the temperature of liquid air as at
room temperature. It is therefore evident that a much great-
er proportion of the recombination energy is radiated at these
low temperatures than at room temperature and that therefore
the device is much more efficient when cooled.

The proceeding discussion indicates that the
infrared output is dependent on the rate of direct recombina-
tion which is proportional to the product of hole density and
electron density. High densities of majority charge carriers
can be provided for in the semiconductive material by the
addition of significant impurities to the material by known
techniques. Large quantities of minority charge carriers can
be injected into the semiconductor by employing point contacts
for junction emitters and by passing current from 10 amp. per
square centimeter to at least 1000 amp. per square centimeter.

The physical arrangement of the units should be such
that the temperature rise due to these high current densities
is kept to a minimum, for example by cooling or by mounting
the unit in an intimate heat transfer relationship with a body
having a large thermal capacity. In this regard one suitable
construction is to form a semiconductive body containing an
n-p junction with massive ends with which ohmic contacts are
made and providing it with a thin intermediate section having
a large ratio of radiating surface to total volume. The p-n

junction in the section should be centrally located and the
lengths of section from the junction to the masses should
be comparable to the drift length of the carrier, i.e. through
which half the injected carriers recombine to provide effective
heat conduction to the heat sinks containing the masses.

SUMMARY

It has been discovered that usable infrared energy
of a narrow frequency band can be produced by electron-hole
recombination across the forbidden band in the semiconductors.
This energy can be induced by passing suitable electrical
currents through the properly prepared materials. It is
advantageous in the operation of semiconductors as infrared
sources that carrier injection concentration be high, that
recombination occur near the surface of the semiconducor and
that it be across the entire energy gap. These characteristics
are obtained by employing good emitters, employing semi-
conducive material having high concentrations of majority
carriers, and employing semiconductive bodies formed so that
a large portion of the recombination occurs near the surface.
Devices of this nature have exhibited high efficiencies based
on the radiated quanta which succeed in getting out of the
sample and the number of electron-hole pairs. They operate
at usable outputs at frequencies having plus lengths of the
order of ten microseconds and they have an essentially
infinite life.

ABSORPTION OF INFRARED LIGHT BY FREE CARRIERS IN GERMANIUM
H.B.Briggs and R.C.Fletcher
Physical Review 91, 1342 (1953)

The absorption of infrared light associated with the presence of free carriers in germanium was measured by injecting these carriers across a p-n junction at room temperature. The absorption was found to be proportional to the concentration of carriers. The absorption as a function of wavelength showed the same sharp maxima previously observed in p-type germanium. These bands were found to change with temperature. An explanation of this absorption was offered in terms of a degenerate energy band scheme.

The presence of donor or acceptor impurities in germanium was found to cause additional absorption of infrared light of a wavelength greater than the fundamental absorption limit of 2 microns.[16,17,18] Some such absorption can be expected according to the classical Drude-Zener theory[19] of the optical properties of free carriers which, in this case, are the holes and electrons released by the ionized impurities. However, the observed absorption is two to three orders of magnitude higher than the Drude-Zener theory would predict. In addition, for p-type germanium, the absorption has structure instead of increasing uniformly with the square of the wavelength as the Drude-Zener theory predicts for this wavelength range. These observations have lead to the performance of two additional types of experiments. First, in order to show that the additional absorption, particularly in p-type germanium, is really caused by the free carriers, the excess absorption caused by free carriers which have been **injected** into the germanium have been measured. Second, the absorption by p-type germanium in thermal equilibrium has been measured as a function of temperature.

The first experiment depends upon the injection of free carriers across a p-n junction when the junction is biased in the forward, or low resistance, direction.[20] If the light, whose absorption is to be measured, is allowed to pass through the sample in a narrow beam parallel and near to the junction, the injected carriers will cause an increase in absorption which can be measured.[10]

A single crystal of germanium containing a junction was finished to a rectangular block 1.5 X 1.0 X 0.4 cm., the plane of the junction being perpendicular to the long dimension. The sides exposed to light were finished plane parallel and polished. The germanium was fitted in a groove in a bakelite mount. The increased absorption caused by the injected carriers was determined by modulating the voltage applied across the junction with a 10 cps rectangular wave obtained from a motor-driven commutater and detecting the rectangular wave of transmitted light with either a lead sulphide photocell or a thermocouple followed by an amplifier and rectifier. This signal was compared with the signal obtained by eliminating the modulation voltage across the junction and inserting a light chopper, driven by the same motor as the commutater at the same frequency, and using the same detection scheme.

Measurements were also made on p-type and n-types samples in thermal equilibrium (normal). Extinction co-efficients for these samples were obtained by the conventional means of measuring the ratio of incident to transmitted light, and using a value for the reflectivity obtained from a separate experiment. The carrier densities were calculated from resistivity measurements using the drift mobilities measured at room temperature for lattice scattering and corrected for impurities scattering according to the Conwell-Weisskopf formula.[21]

The temperature dependence of the absorption of the several p-type samples was measured by putting the sample in contact with a copper block, which was cooled by an appropriate refrigerant. Higher temperatures were obtained by passing heavy currents through the samples. Temperatures were measured with an iron constantan thermocouple attached by pressure contacts to the samples.

The simplest way to explain the direct proportionality between the absorption and the concentration of the carriers is to assume that the extra absorption observed in the infrared is caused by the free carriers, whether they be introduced by ionization, chemical impurities, or whether they are injected across junctions.

Two other possibilities were considered to explain the observed proportionality. First, the absorption might be associated with the normal ionized acceptor and donor impurities. This absorption would be proportional to the number of such impurities present and would thus explain the observed proportionalities in normal samples. However, the fact that injected carriers have the same absorption eliminates this as a possibility. In addition, experiments were carried out with compensated samples in which the carrier density was not proportional to the impurities. In these the absorption was found to be proportional to the carrier concentration and not to the impurity concentration.

A second possibility is that the absorption is associated with impurities other than the impurities governing the electrical resistivity or with crystal imperfections. These are assumed to introduce an energy level into the forbidden band from which either electrons or bodies can be excited by absorbing light. This possibility is suggested particularly by the absorption bands observed in the p-type germanium. In order that this absorption be proportional

to the carrier concentration it must be assumed that the
carriers change the population of these levels. For
example, consider the absorption caused by ionizing a hole
trapped on an impurity level. In this case the absorption
will be proportional to the number of empty impurity levels.
If the Fermi level is above the impurity level, the relative
population of levels in the impurity level and in the valence
band will be governed by a Boltzmann distribution. That is,
the number of empty impurity levels in thermal equilibrium
will be proportional to the number of free holes. This would
explain the observed proportionality between the absorption
constant and free holes.

When carriers are introduced by injection, however,
the holes are not in thermal equilibrium, and we would expect
that the ratio of empty impurity levels to free holes would
be considerably different. The fact that the cross section
for injected carriers is the same as that for carriers in
thermal equilibrium strongly suggests that the absorption is
not caused by impurities or imperfections. Moreover it should
be pointed out that in order for the cross section to remain
constant from sample to sample, the concentration of impurity
levels has to remain constant. Every sample tried had
essentially the same cross section. This same cross section
was also measured on samples prepared in other laboratories
with different doping materials.

It should be observed that, in order for the absorption
to be ascribed to empty energy levels in the forbidden band, the
cross section for capture of protons by these empty levels is
required to be extremely large.

The authors did not believe that the extra absorption
beyond the fundamental absorption edge could be associated with
the normal acceptors or donors because the cross section measured

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in normal samples was the same for (1) injected carriers,
and (2) compensated samples. They did not believe that it
was associated with impurities or imperfections because (1)
the cross section was the same for injected carriers, (2) the
concentration of such uncontrolled impurities was required to
be the same for different samples and (3) too large a cross
section was required. They believed the most reasonable
explanation for the extra absorption was that the big carriers
themselves were absorbing the light by some mechanism other
than that proposed by the simple Drude-Zener theory.

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