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THE "THYRISTOR"- A NEW HIGH-SPEED SWITCHING TRANSISTOR

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THE "THYRISTOR" –

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Approved

Stuart W. Seeley

This bulletin presents a description of the construction and characteristics of a versatile and novel semiconductor device, called a "Thyristor" that may be operated, either as a bistable element switching to a high conductivity mode, or as a more conventional high–frequency transistor, either in switching or amplifying circuitry. The "Thyristor" has thyratron–like characteristics that closely approach those of an ideal switch. However, the "Thyristor" unlike the thyratron, can be turned off readily by the control element.

The open–state current is about 2 microamperes and the closed–state voltage drop is 0.3 to 0.5 volt. The unit can be switched into the high–conductance mode in less than 0.1 microsecond with a pulse energy of 10^{-4} ergs. It can be turned off with a pulse energy of about 10^{-1} ergs in times of the order of 0.1 microsecond.

The bistable operation depends upon a new type of semiconductor contact that collects holes at low current densities and injects electrons at high current densities. The electron alpha of the injector increases as a power–law function of current and greatly aids in obtaining device reproducibility. These injector properties can be described in terms of a tunneling mechanism.

Introduction

The use of the transistor as an electrical switch has long been attractive. In fact, the point-contact transistor was generally a better switch than an amplifier to the dismay of circuit engineers seeking amplification. The point-contact transistor has a current transfer ratio (alpha) greater than unity and this characteristic can be utilized in circuits to provide a negative resistance and bistable operation. When junction transistors having an alpha less than unity were developed, their use vastly improved the stability of amplifiers.

Junction devices having alphas greater than unity have been described and include the avalanche transistor [1,2,3] and the p-n-p-n hook transistor. [4,5] More recently a silicon diode p-n-p-n switch in which the alpha increases above unity with current due to the saturation of recombination centers was discussed in considerable detail. [6] The device discussed in this bulletin also has a current transfer ratio which becomes greater than unity with increasing current. In the present case this behavior depends on a new type of semiconductor contact that collects holes at low current densities and injects electrons at high current densities.

Because of its thyratron-like properties the device has been named "Thyristor". The "Thyristor" however, is markedly superior to the thyratron in many of its properties. For example, the unit can be turned off by the base with low energy pulses in less than 0.1 microsecond, and the total voltage drop across the unit is a few tenths of a volt.

"Thyristor" Geometry and Fabrication

A cross section of the "Thyristor" is shown in Fig. 1. Arsenic is diffused into a 3 ohm-cm p-type germanium wafer to form an n-type base region. A circular mask is applied and the unnecessary n-type skin is etched away, thus forming a circular plateau about 0.013 inch in diameter. Up to this point the structure is similar to that described by Lee. [7] An emitter junction and an ohmic base connection are soldered to this plateau in a hydrogen atmosphere. The emitter dot is an alloy of indium and aluminum. The base wire is soldered to the germanium using a lead-tin-antimony alloy. The emitter is about 0.004 inch in diameter. The area of the base connection is determined by the size of the wire used and the

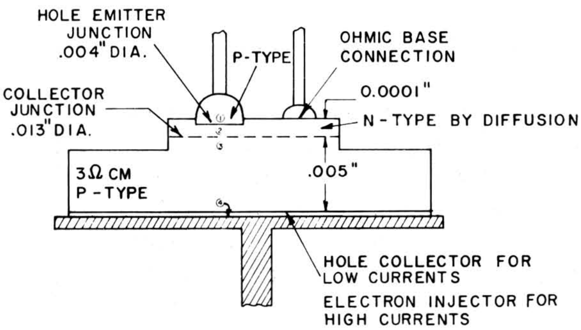


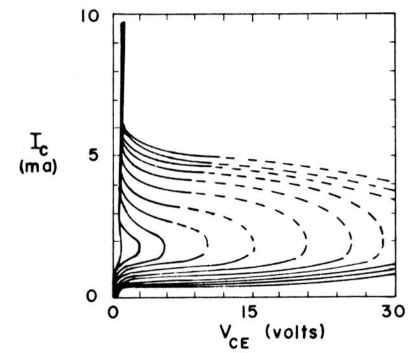
Fig. 1 – Cross section showing construction

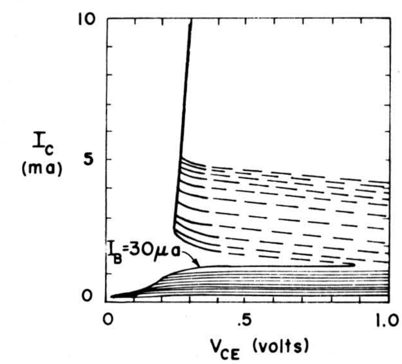
amount of solder present. The amount of material used must be accurately controlled to prevent shorting through the thin base layer. However, after the operations are properly set up, reproduction of the units can be accomplished readily.

The collector connection is made by soldering, at a temperature of 300°C to 400°C, a nickel tab to the germanium of the collector with an alloy of lead, tin and indium. The connection may cover the entire area of the germanium wafer and does not involve any difficult or exact mechanical process. However, the physical nature of this contact has an important bearing on the "Thyristor" characteristics as discussed later.

If desired, the "Thyristor" can be used as a normal, non–regenerative, transistor switch by restricting the collector current to values below the breakover current. However, the new and interesting mode of operation occurs when the collector current is allowed to rise above a designed critical value. As the collector current is increased, the total current transfer ratio, α_{ce}, increases. When α_{ce} becomes greater than unity, for the grounded–emitter connection a large increase of current occurs and and the voltage across the unit drops to a very low value as shown in the characteristic curves[8] of Fig. 2(a) and (b). A short pulse, approximately 50 millimicroseconds in length, may be used to switch to the high conductivity mode. The transition to this mode is regenerative. After reaching the high current region, the base current can be removed without affecting the collector current. However, by the use of a reverse voltage between emitter and base, the high current can be turned off.

The "off" current is about 2 microamperes at room temperature and collector–to–base breakdown occurs at about 60 volts. In the high conductance mode the device displays a series resistance of about 3 ohms, between emitter and collector and for 100 milliamperes of collector current the voltage drop is only 0.5 volt. The small power dissipation in the high conductance mode is to be noted. The important parameter determining the transition to the high conductivity mode is the collector current. The transition value of this current is called the breakover current.





(b.) Curves for I_B = 0 to 30 μa in 10 equal steps

Fig. 2 – Collector characteristics

In Fig. 3, α_{ce} is shown as a function of emitter current. Since collector current is inversely proportional to $1-\alpha_{ce}$ with the emitter grounded, the collector current would tend to rise to infinity when α_{ce} equals unity. Under this condition the device enters the high conductance mode and the current must be limited by external resistance. Note that when α_{ce} begins to rise, it increases very rapidly with emitter current. This total α_{ce} can be broken up into two parts, α_{holes}, which expresses the hole current–transfer–ratio across the base for holes injected at the emitter, and $\alpha_{electrons}$, the electron current transfer ratio across the collector body for electrons injected at the special collector connection. To measure the hole and electron alphas separately, a special transistor was constructed as sketched at the top of Fig. 4. The hole alpha (Fig. 4) shows the familiar shape and falls off at high current density. The electron alpha, plotted in Fig. 5, is small at low values of I_E. However, it increases rapidly with I_E. Between 1 milliampere and 5 milliamperes an increase of two orders of magnitude occurs. The electron α exhibits a power law dependence on the current. This power law relationship is a desirable feature because it gives a sharp threshold to the turn–on current.

It has been shown that when $\alpha_{ce} \geqslant 1$ the device will break over into the high conductance mode. In this mode the junctions have effectively disappeared. There is injection of holes from the emitter and injection of electrons from the collector contact in very nearly equal numbers. The flow in the intermediate regions (2 and 3 in Fig. 1) is due primarily to the electrical field (which no longer appears only at the collector junction.) A linear voltage–current relationship is observed in this condition in which the resistance presented by the transistor (collector to emitter) is about 3 ohms.

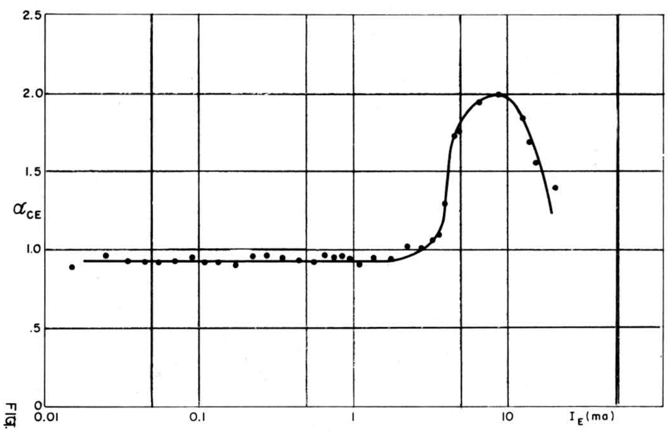


Fig. 3 – Behavior of α_{ce}

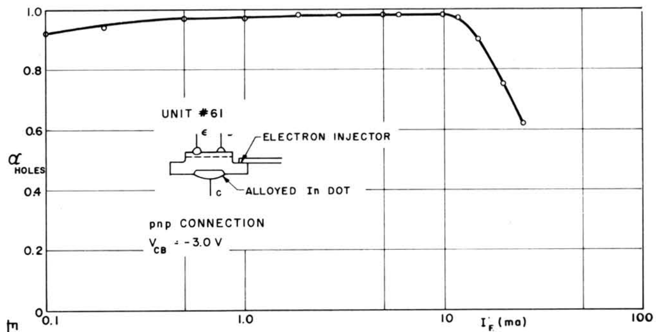


Fig. 4 – Behavior of α_{holes}

A slow response for the transition time into the high conductance mode might be expected because the transport of electrons (minority carriers) across the 5-mil collector body, (region 3 of Fig. 1) is involved. The expected transport time, if due to diffusion, would be $\tau_d = w^2/D_n = 1.5$ microseconds. Actually, however, the electron transport is primarily due to an electric field. The expected transit time for this is $\tau = w^2/\mu V = 0.1$ microsecond. This is approximately equal to the measured time required to switch into the high conductance mode. The energy required to turn on the unit with pulses is small, about 10^{-4} ergs.

The time required to switch off the high conductance mode involves storage effects. The high charge densities, corresponding to a current of the order of 10^3 amp/cm^2 in the active region under the emitter must be altered to apply a reverse bias at the emitter junction. The base lead resistance hinders this effort. The pulse energy for turning the unit off is about 0.1 erg. The time required is of the order of 0.1 microsecond.

Response times of the "Thyristor"

One of the most important parameters in a negative resistance switching device is the speed of response. Measurements reported here were restricted to times of 20 millimicroseconds in length or longer, because of equipment limitations. The "Thyristor" is characterized by two types of switching response times, one for the linear mode and one for the bistable operation. In the linear mode the transistor displays the rapid response expected from a device with an alpha cut–off frequency of about 100 Mc. The rise and fall times in a grounded–emitter circuit were better than 20 millimicroseconds. Storage times were not in evidence because the unit was not driven into the saturation region in attaining these speeds.

Nature of the Electron Injector (Collector Contact)

In the preceding discussion attention has centered mainly on the electrical behavior of the device. In this section the physical nature of the all–important collector contact is considered. Since electron injection is an important function of this contact it has been termed the electron injector.

To test for a rectifying barrier between the collector body and the electron injector, special devices were made with an additional contact as sketched in Fig. 6. The V–I characteristic of the same figure shows that there is no ordinary rectifying p-n junction at the electron injector interface.

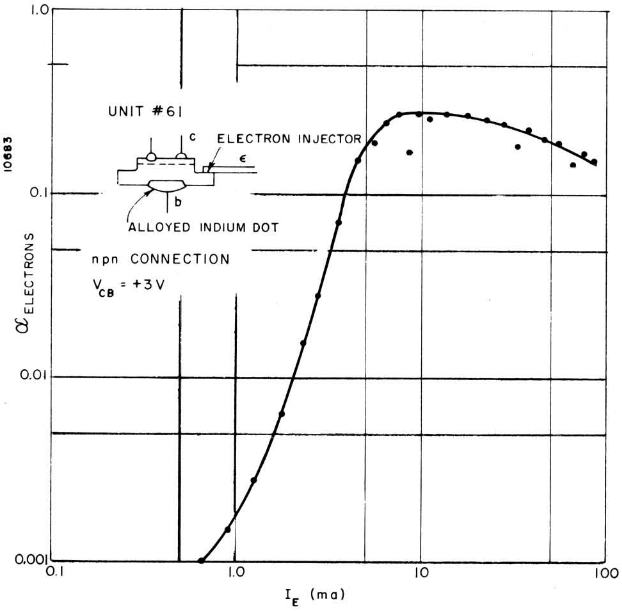


Fig. 5 – Behavior of $\alpha_{electrons}$

Note that positive and negative voltages are plotted. The contact is ohmic (~100 ohms) until electron injection becomes significant. This behavior is consistent with a tunneling mechanism described later.

An attempt to examine the nature of the barrier at the electron injector using photoelectric measurement techniques indicated bending of the band edges at the electron injector contact toward n-type and indicated that the barrier voltage was at least 3 kT/q. The height of the barrier could not be determined because it was impossible to saturate the region beneath the soldered connection with light–generated pairs.

The relationship of the "Thyristor" geometry to the p-n hook structure[4,5,6] is of considerable interest. The hook structure can give a negative resistance characteristic similar to the one described in this bulletin. Although the form of the characteristic curves is the same, the break–over current, switching speed, and the operating temperature range can differ considerably. These differences stem from the nature of the electron injector.

To observe p-n-p-n hook operation with the "Thyristor" geometry, units were built similar to the unit shown in Fig. 1. The collector connection, however, was the lead–arsenic eutectic alloyed at 600°C. Thus, an n-type germanium region was produced at (4). With this structure the type of characteristic shown in Fig. 2 could not be obtained since breakover to the high conductivity mode occurred at low currents. Typical values for the point of breakover under d-c conditions are: I_B =1-10 microamperes; I_{CB} =10-50 microamperes.

This low breakover current causes two operating difficulties. First, the allowable temperature range is greatly reduced because of the increase in I_{co} with temperature. Since breakover occurs at a low value of collector current, for example, the top operating temperature with zero base current is low, about 35°C compared to 65°C for typical "Thyristors." It is possible to operate both types of transistors at higher temperatures by using a reversed base bias. Operation up to 85° C has been observed. For this type of operation the p-n-p-n unit is a "normally closed" or "on" switch; a base current and stand–by power are necessary to hold it open at temperatures above 35°C.

Secondly, since the low value of the breakover current is accompanied by a very small field across the collector body, the field acceleration of the minority carriers through the collector will not be very effective. The speed of response then depends upon diffusion flow. To obtain fast transit times with diffusion flow a much thinner collector body is necessary.

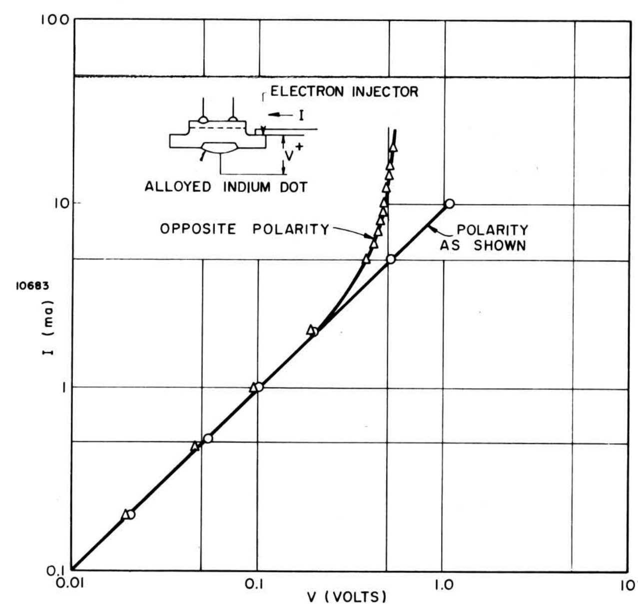


Fig. 6 – Voltage-current characteristics of electron injector

The Tunneling Mechanism

The characteristics illustrated in Fig. 6 indicate that there is no ordinary junction at the electron injector. A tunnel–effect mechanism, is a possible explanation for both the resistive nature of the inface at zero bias, and the behavior of the electron injection efficiency as a function of current.

The energy band picture at the electron injector is shown in Fig. 7. Changing the amount of indium in the alloy changes the barrier and the breakover current. For small values of current, holes tunnel through the barrier; there is a small resistance at the interface (in addition to the series body resistances). As the hole current increases, the barrier height is decreased. The electron current, which is in thermal equilibrium under conditions of zero flow, will increase as the barrier is decreased. Since the electron and hole currents display different dependences on the barrier height (owing to the different mechanisms involved) there is a change in the relative proportion of hole–to–electron currents as the total current increases. This tunneling mechanism leads to an electron injection efficiency with a power law dependence on the total current through the device.

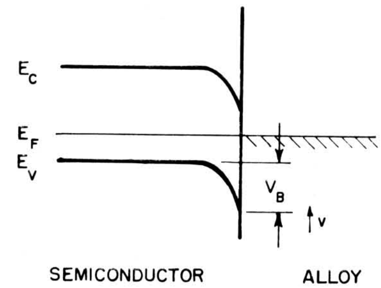


Fig. 7 – Energy level diagram at electron injector

Conclusions

The advantageous features of the "Thyristor" are summarized below.

1. The device is capable of switching times of the order of 100 millimicroseconds.

2. It has a low sustaining voltage, of the order of a half volt at 100 milliamperes. This results in low power dissipation in the high conductivity mode.

3. The structure can dissipate high powers.

4. The negative resistance characteristic allows the use of simple circuitry for switching.

5. Fabrication and alignment are simple and can be carried out with ordinary diffusion and alloy techniques.

6. Transistors that do not have a high conductance mode, or that enter this mode at any desired current level, can be made by simple changes in a soldered contact.

The novel feature of the "Thyristor" is the electron injection at the collector contact. For best operation and device reproducibility, the electron injection should increase rapidly with current. A novel contact has been developed that exhibits this desired characteristic, giving a power law increase of electron injection as a function of current. The properties of this contact can be described in terms of a tunneling mechanism.

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8 The characteristics of Fig. 2 are taken from photographs of 60 cps oscillograph traces.