H. N. Yu

The Chargistor, a New Class of Semiconductor Devices

This correspondence will describe a new class of semiconductor devices called Chargistors. Each device is composed of a bar of either *p*-type or *n*-type high resistivity semiconductor material to which a number of rectifying contacts or control electrodes are attached. The conduction through the bar due to hole injection at one end and electron injection at the other is limited by space charges. The space-charge regions exist because both holes and electrons recombine in the intrinsic body. The potential and space-charge distribution in the body can be changed by the action of the control electrodes which cause the current flow to be modulated. The characteristic curves of these devices were observed to be similar to those of vacuum tube triodes, tetrodes, and pentodes, which indicates that the control electrodes behave in a similar manner to grids.

Basic configuration

The basic working model of a triode Chargistor as shown in Fig. 1(a) was made of a slab of high resistivity *n*-type germanium bar (resistivity$\approx$45 ohm-cm, lifetime$\approx$200 μsec) with the dimensions of $0.010\times0.030\times0.200$ inch. All three electrodes, the *p*-type "charger," the *n*-type "feeder," and the *p*-type "gate" are alloyed on one surface of the bar. Indium was used for the *p*-type contacts and lead-tin-arsenic was used for the *n*-type contact. The *p*-type gate electrode was placed somewhat closer to the *n*-type feeder electrode in order to obtain high transconductance. Contacts were alloyed in the form of strips having dimensions of 0.010×0.030 inch. Even though dots with the diameter of 0.010 in. have been used, it was found that when strips were used the units were more reproducible.

With positive voltage input to the *p*-type gate, the output V_c-I_c characteristics of the *p*-type charger are shown in Fig. 1(b). The dotted lines in the same Figure show the corresponding family of input current versus output voltage. Negative resistance as well as constant-current characteristics are obtained. These characteristics can be used for applications associated with switching, amplifying, and oscillating circuits. Figure 1(c) shows the output V_c-I_c characteristics when the input is open-circuited, short-circuited, and when the output conductance is saturated. The active operating range of the device lies between the short-circuited curve and the saturation curve, which are analogous to the cut-off curve and the saturation curve of a transistor or a vacuum tube.

Principle of operation

The operation of the Chargistor relies on electrostatic potential shielding as well as on the conductivity modulation effect caused by space-charge variations. The forward-conduction phenomenon of a PIN diode has been the subject of many investigations. Recent work of Lampert and Rose[1] has shown that space-charge buildup due to recombination of holes and electrons in the intrinsic body has limited the injected plasma density[2] even though the space-charge, due to excess charge car-

Figure 1a **A triode Chargistor.**

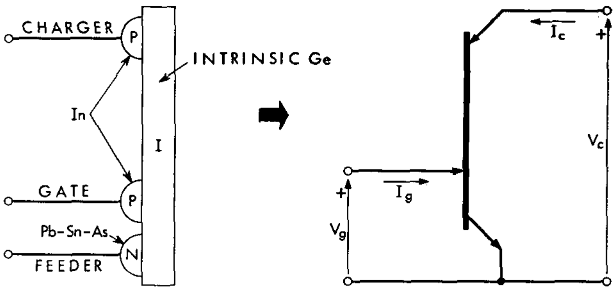
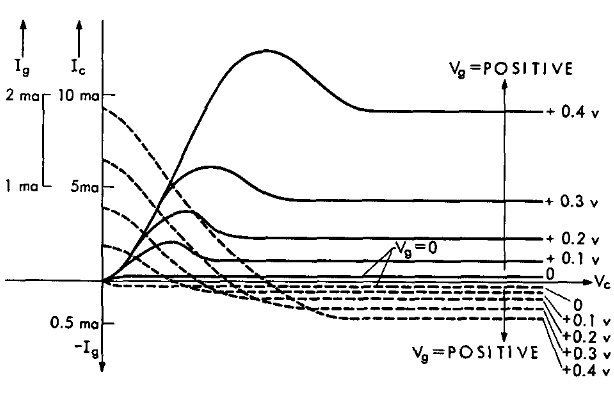


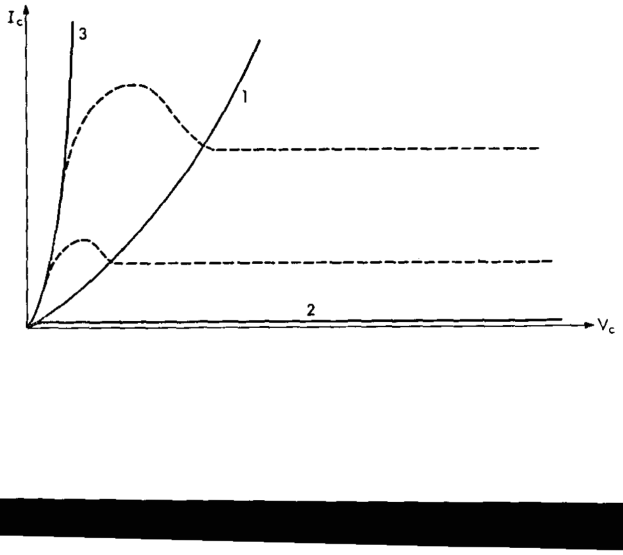
Figure 1b **Output V_c-I_c characteristics of a triode Chargistor.**



riers over the plasma, is a relatively small quantity as compared to the plasma density. Kleinman[3] has shown that, in the case of a PIN diode with a short *I*-region, the *V-I* characteristic is expected to be similar to a *pn* junction diode since the conductivity of the short intrinsic region is fully modulated by the injected carriers. The possibility arises that if the space-charge due to excess carriers over the plasma could be compensated, the conduction through the PIN structure could be greatly increased. When a hole-injecting contact is placed in the region where excess electrons or negative space-charge exists, the injected holes tend to neutralize the excess electrons and thereby cause the conductivity to be increased. When the output voltage, V_c, is raised, the potential in the intrinsic body becomes sufficiently high to cut off the injection from the gate contact. In the transition region, negative resistance is observed.

When the gate contact is blocked from injecting carriers, the Chargistor action enters another region where the output current becomes constant regardless of the output voltage change. Since both the charger junction and the feeder junction are forward-biased at all times, the constant-output current characteristic would imply that the gate, under this condition, is acting like a grid of the vacuum tube in shielding the potential variation from one part of the body to the other. The potential distribution throughout the intrinsic body has been detected by a potential probe on a free surface of the bar for several values of the output voltage. A typical set of potential-distance curves is shown in Fig. 2. The potential of the intrinsic body in the vicinity of the gate junction assumes a value close to that applied at the gate and stays constant for different charger voltages. The electrostatic potential shielding by the gate junction is very effective. The shielding action of the gate junction is responsible for the constant-current output characteristics. Since the potential drop in the section between the gate and the feeder ($V_{gF}=V_g$) stays constant with respect to V_c, it is obvious that the current flowing in the bar is controlled by V_{gF}. Unlike the ordinary field-effect transistor,[4] in which the transistor action depends upon the pinching effect by expanding the depletion region of the gate-channel junction, the Chargistor action depends upon the electrostatic potential shielding effect through the gate junction. In the case of the field-effect transistor, zero bias at the gate yields maximum output current, whereas in the case of the Chargistor, zero bias at the gate yields minimum output current or cut-off condition. The effect of the gate junction of the Chargistor is therefore definitely different from that of an ordinary field-effect device.

Figure 1c **Output V_c-I_c characteristics of a triode Chargistor with (1) *Input open-circuited*, (2) *Input short-circuited*, and (3) *Output conductance saturated*.**



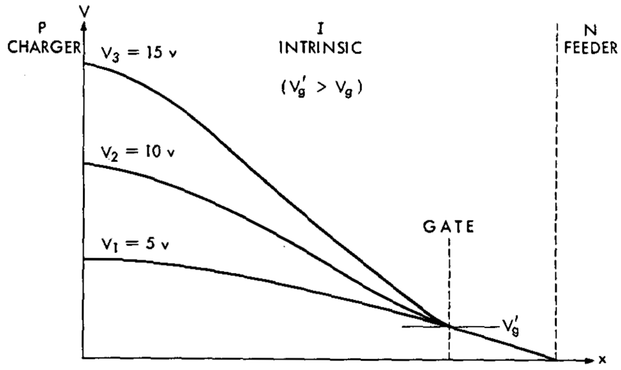


Figure 2 **The potential-distance plots in the intrinsic region of a triode Chargistor for three different charger voltages with *constant* gate voltage (V_g).**

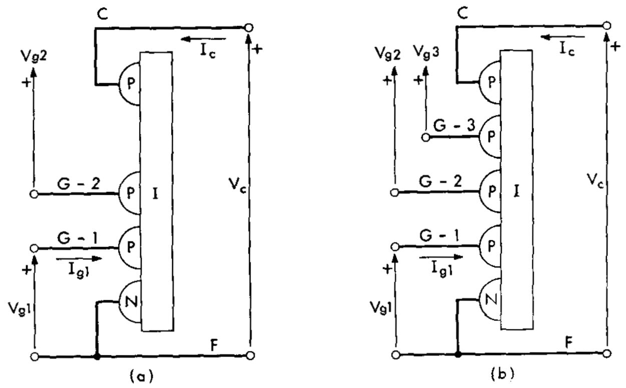


Figure 3 **(a) Tetrode Chargistor, (b) Pentode Chargistor.**

Tetrode and pentode

The idea of the electrostatic potential shielding effect has been extended further by employing a number of gates. Tetrode and pentode Chargistor devices can be constructed as shown in Figs. 3(a) and 3(b). The description of the complete behavior of such devices is beyond the scope of this correspondence. However, the additional control by the extra gate electrode in the case of a tetrode Chargistor was found to cause the electrostatic potential shielding effect to be more effective.

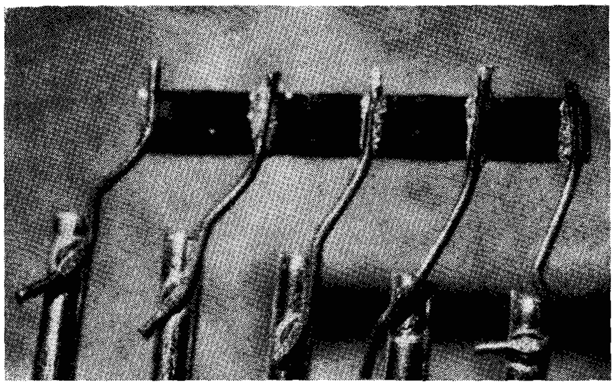


Figure 4a **Photograph of an experimental pentode Chargistor.**

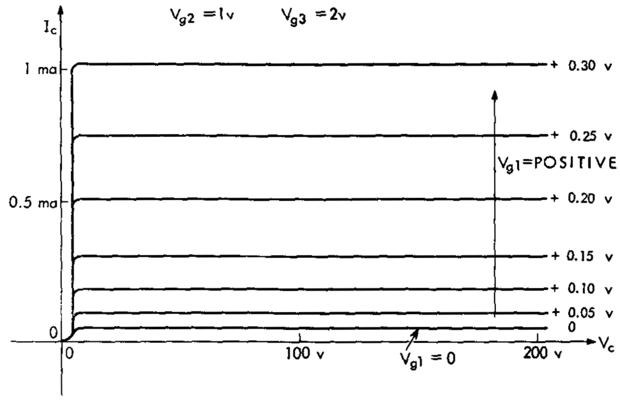


Figure 4b **Typical output V-I characteristic of a pentode Chargistor.**

Also, the gain of the device can be controlled by varying the constant-voltage bias applied to Gate-2 electrode. In the case of a pentode, the various parameters can be controlled further by varying the constant voltage bias at either Gate 2 or Gate 3. Under some bias conditions, negative transconductance can be obtained in both the tetrode and the pentode Chargistors. The negative resistance region which is observed in the triode can also be controlled through biases applied to Gate 2 and Gate 3.

The number of electrodes which can be employed and the different geometries which can be used will make the Chargistor device versatile in its functional capabilities. Electrically complementary units with *n*-type gate electrodes closer to the *p*-type feeder on the same basic PIN structure have also been constructed and proved successful. A picture of an actual pentode Chargistor and its typical output *V-I* characteristic are shown in Figs. 4(a) and 4(b).

Terminal characteristics

Ordinarily, when intrinsic semiconductor material is used in a device, it is expected to be very sensitive to temperature variations. It has been found that the power dissipation of several units under test was so high that the temperature of these units reached the melting point of indium. As a result, the germanium crystal dropped from the mounting stems with little variation in the observed output characteristics while the heating was taking place. When a heat sink was provided, a similar device was operated at two watts with a peak current of the order of 0.5 ampere for several hours without any detectable deterioration of its characteristics. When good electrostatic potential shielding is obtained, the output impedance of the device has been observed to be as high as 20 megohms and the operating voltage as high as 200 volts without any noticeable breakdown effect. The high-voltage operation capability of the Chargistor device is primarily due to the shielding effect which causes the potential drop to occur in the section of the intrinsic body between the charger and the gate. As a result, the gate junction does not sustain the entire voltage applied across the body, whereas in the case of a transistor, the collector junction sustains the entire voltage applied to the collector electrode. Chargistor operation beyond 200 volts is definitely possible. In practice, power gain of the order of 50 db has been obtained in a small-signal amplifier circuit with one Chargistor device.

With the Chargistor device described, the operation extends from dc to the submegacycle range. The frequency of oscillation with a typical device is about 200 kc/sec at room temperature. No theoretical limit on the frequency response of the Chargistor device has been established, although there are reasons to believe that the frequency response of such a device will be lower than that of a transistor. The Chargistor device has also been found to be sensitive to light as well as to magnetic field.

The author is indebted to Dr. A. B. Credle for his support and interest in the exploratory program. He also wishes to thank E. W. Bauer, H. S. Yourke and Dr. J. W. Horton for their encouragement and numerous discussions. The help of Messrs. J. F. Schomburg, R. J. Lynch and Mrs. I. J. Eich in the initial phase of the experimental work is also acknowledged.

References

1. M. A. Lampert and A. Rose, "Volume-Controlled, Two-Carrier Currents in Solids: The Injected Plasma Case," *Phys. Rev.* **121,** 26 (1961).
2. The "injected plasma density" referred to here is the condition in which the hole density is the same as the electron density. This injected plasma density is due to double injection of holes and electrons into the solid material.
3. D. A. Kleinman, "The Forward Characteristics of the P-I-N Diode," *Bell System Tech. J.* **35,** 685 (1956).
4. G. C. Dacey and I. M. Ross, "The Field-Effect Transistor," *Bell System Tech. J.* **34,** 1149 (1955).

Received August 9, 1961