B. G. Streetman
N. Holonyak, Jr.

Current Oscillations in Deep-level Doped Semiconductors*

Abstract: We observe current oscillations in p-i-n (and optically excited n-i-n) devices containing deep levels. The oscillations occur in the positive resistance region of the space-charge-limited (SCL) current regime of the *I-V* characteristics, before the occurrence of double-injection breakdown. This is a general effect, occurring in Si, Ge, and GaAs compensated with various deep-level impurities and in electron-irradiated devices. The oscillations are sinusoidal at threshold, with frequency strongly dependent on the recombination kinetics of the i-region, and on the deep level density, but are essentially independent of device length. The frequency and amplitude of the oscillations are affected by temperature and optical excitation. Various models have been proposed to account for oscillations in semiconductors containing deep levels, but no existing model describes fully the various aspects of the effect reported here. Because the device length exceeds carrier diffusion length, any model for the oscillation mechanism must include the existence of space charge and the kinetics of recombination, but may not depend essentially upon a traveling domain which imposes a length dependence on the oscillation frequency. Tentatively, we favor a model in which the recombination process unbalances the steady or dc space charge.

Introduction

It has been known for several years that semiconductors carrying space-charge-limited (SCL) currents can exhibit oscillations in positive resistance regions of the *I-V* characteristics.[1] These oscillations occur in p-i-n, n-i-n, and p-i-p devices which contain deep-level recombination or trapping centers. At the time of this writing, oscillations of this general type have been reported in Si doped with Au,[1,2,3] Co,[1,2,4] and Zn,[1,5] in Ge doped with Au,[6] Cu,[7] Mn,[8] and Zn,[9] in electron-irradiated Si[10] and GaAs,[10] and in semi-insulating,[1] Cr[11]- and oxygen-doped GaAs.[11] In spite of the obvious generality of the effect, no acceptable theory has been completed to explain the oscillation mechanism. The purpose of this paper is to bring together the various experimental observations and to indicate the requirements which a model for the oscillations must satisfy.

Experimental observations

Typical SCL characteristics for a Au-doped Si p-i-n device are shown in Fig. 1. The Au density in this device is sufficient to lock the equilibrium Fermi level (E_F) at 0.44 eV above the top of the valence band (E_v), between the Au donor and acceptor levels. At low voltages, after a brief ohmic region, the current follows the V^3 dependence

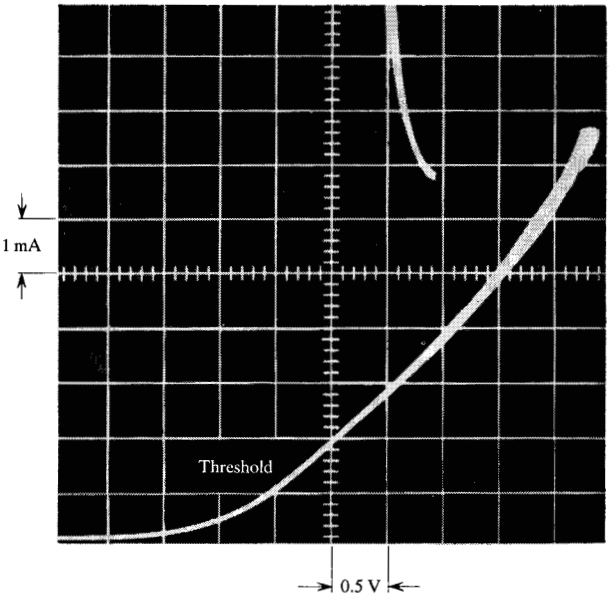


Figure 1 *V-I* characteristic of a Au-doped Si p-i-n device, showing the cube-law characteristic, the oscillation range, and the double-injection breakover. (Adapted from figure in Ref. 3).

predicted by Lampert and Rose[12] for double injection into a semiconductor,

$$J = \frac{125}{18}\,\epsilon\mu_n\mu_p\tau\,V^3/L^5, \qquad (1)$$

* This work has been supported by the National Science Foundation (Grant GK-2657) and the Advanced Research Projects Agency (Contract SD-131).

B. G. Streetman and N. Holonyak, Jr. are located in the Department of Electrical Engineering and Materials Research Laboratory at the University of Illinois, Champaign-Urbana, Illinois 61801.

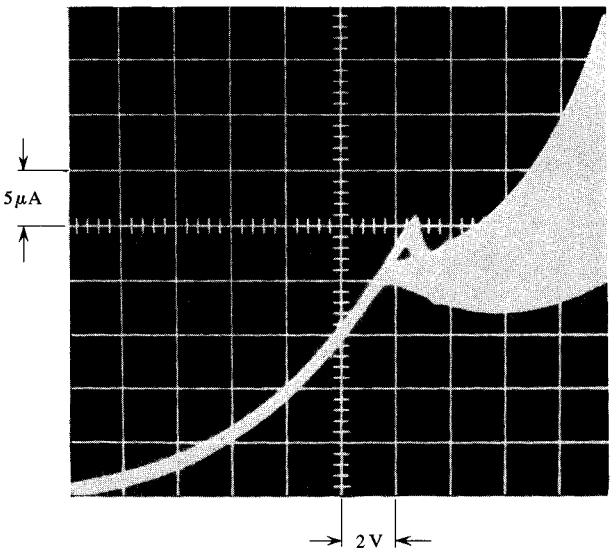
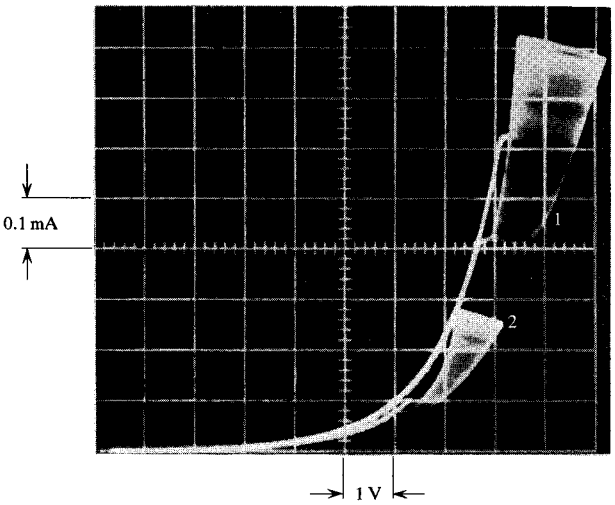


Figure 2 *V-I* characteristic of a Co-doped Si p-i-n device. (Adapted from a figure in Ref. 4).

Figure 3 *V-I* characteristics of a 1-MeV electron-irradiated Si p-i-n device, measured at two temperatures: (1) 250°K, (2) 242°K. (Adapted from a figure in Ref. 10).



where J and V are the current density and the sample voltage, respectively, ϵ is the dielectric constant, μ_n and μ_p are the electron and hole mobilities, τ is the carrier lifetime, and L is the length of the i-region.

At a bias of 5V for the device shown double injection breakover occurs, which is typical of materials for which the carrier lifetime increases at high levels of injection.[13] Between these extremes, i.e., between low injection levels and the levels at which lifetime changes are important, is a region over which current oscillations occur. The onset of oscillations (threshold) accompanies a deviation in the cube-law characteristic; above threshold, the current increases with less than cube-law voltage dependence. This deviation, or notch in the *I-V* characteristic, is more apparent in devices for which trapping is appreciable—for example, Co-doped Si samples in which E_F is above the upper Co level (Fig. 2). In this figure the onset of oscillations accompanies a temporary decrease in the average current, indicating an increase in the effective impedance of the device as the oscillations begin. Once the oscillation condition is established, it persists as the current is lowered to well below the threshold value. This hysteresis effect suggests that in this device the onset of oscillations requires a certain condition of occupancy of the Co trapping centers, and this condition is maintained in the oscillation regime as the average current is lowered. Similar effects are observed in the electron-irradiated Si device of Fig. 3.

A strong temperature dependence of the oscillation threshold is evident in Fig. 3. In all of the devices for which temperature dependences have been reported, the threshold frequency and current both decrease with decreasing temperature.

The frequency of the oscillations is a strong function of the type of deep levels dominant in the i-region of the structure. Frequencies range from 10 to 100 MHz in Au-doped Si devices to 1 to 500 kHz in Zn-doped structures, depending upon the impurity density and temperature. The most reliable data relating threshold frequency and impurity density come from the Au-doped Si devices, since the Au density can be varied while keeping the Fermi level essentially locked at $E_v + 0.44$ eV. Moore et al.[3] report that the room-temperature threshold frequency varies linearly with the Au concentration, and the period of the oscillations is approximately the electron lifetime in the material. This suggests that the oscillation mechanism is intimately related with the more usual recombination processes occurring in space charge neutral structures or regions. We have recently observed a similar linear dependence of frequency on total dose for electron-irradiated Si devices, for which E_F approaches the intrinsic level at large doses. No simple relationship between frequency and impurity density has been observed for impurities other than Au, since variation of the doping density also changes the equilibrium Fermi level (and thereby alters the initial occupancy of the recombination and trapping centers).

In addition to the impurity-density dependence, the oscillations are strongly affected by the injected carrier densities. Moore et al. suggested the existence of a critical carrier density for oscillation in Au-doped Si devices, and Blouke et al.[5] have recently shown that the temperature dependence of oscillation frequency in Zn-doped Si follows that of the reciprocal of the carrier concentration at threshold (Fig. 4). The values of $1/n_{x0}$ plotted in Fig. 4

represent the inverse of the carrier concentration at the position within the i-region for which the injected electron and hole densities are equal. Using the measured threshold voltage at each temperature and the cube-law theory of Lampert and Rose,[12] we calculate the concentrations n_{x0} from the expression[5]

$$n_{x0} = \frac{50}{9}\,[\epsilon\mu_n\tau\, V^2/q(b + 1)L^4], \qquad (2)$$

where q is the electronic charge and b is μ_n/μ_p.

The frequency of oscillation is not a function of device length. However, we observe in both Au- and Zn-doped Si devices that the threshold voltage varies as the square of the length of the i-region. From earlier data[3] and from Fig. 4, the critical parameter appears to be injected carrier density rather than a simple transit time. As the device length is varied, the threshold voltage adjusts accordingly to maintain the critical carrier density required for oscillation. This dependence of threshold voltage upon carrier density is substantiated by optical excitation experiments.[4]

Requirements of a model

Any satisfactory model for the oscillations must take into account the critical roles of the space charge and the carrier recombination kinetics. Many of the oscillation models proposed by Konstantinov et al.,[14] Bonch–Bruevich and Kalashnikov,[15] and others involve recombination but do not require the existence of a space-charge region. Experimentally, however, the oscillations are observed only when regions of positive and negative space charge are separated spatially (this includes the illuminated n-i-n devices and devices with "ohmic" contacts). Theories which involve a simple transit time owing to propagation of space charge waves or "recombination waves" cannot be applied, since experimentally frequency is independent of device length. The average electric field at threshold is often as low as a few hundred V/cm, which rules out hot carrier effects. The generality of the effect and the fact that the oscillations are often pure sinusoids discourage belief in such relaxation effects as filaments which build up electrically and relax thermally. Any such theory would have to be general enough to be operative over an extremely wide impurity doping range.

A qualitative oscillation model

We are currently considering a model which involves the periodic fluctuation of space charge in alternate regions of the p-i-n structure (Fig. 5). The values of p and n sketched in Fig. 5(a) represent the free carrier concentrations as calculated from the Lampert and Rose treatment. The steady state space charge at position x, measured from the p-contact, is obtained from[5]

$$p - n = \frac{20}{9}\,(\epsilon V/qL^2)(1 - 2x/L). \qquad (3)$$

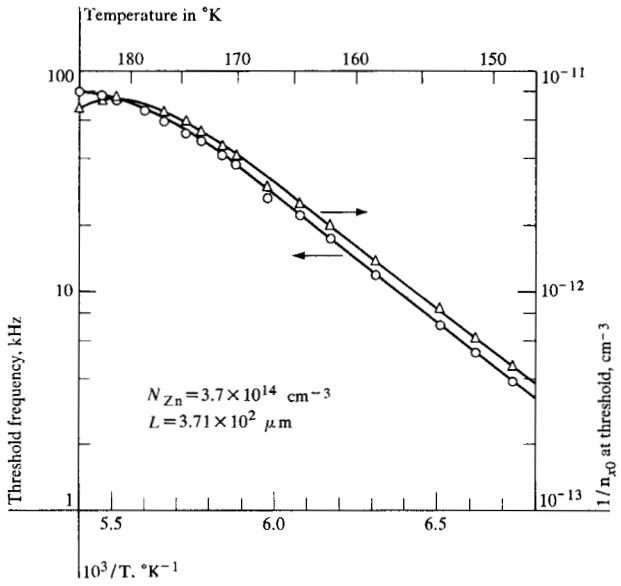
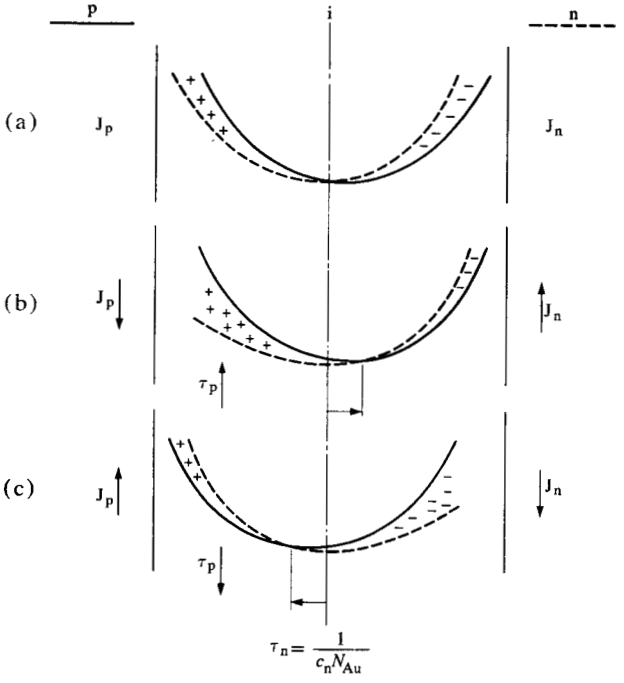


Figure 4 Threshold frequency and inverse carrier concentration versus inverse temperature for a Zn-doped Si oscillator.[5]

Figure 5 Electron and hole distributions in a p-i-n device: (a) steady state; (b) and (c) departures from steady state.



Although this theory neglects trapping, it does illustrate the effects of space charge on the free carriers. In the steady state case, positive space charge exists near the p contact, because some electrons injected at n are lost by recombination before they can drift across the device to

compensate the injected holes. Similarly, some holes recombine before they reach the n-side of the i-region, which results in a net negative space charge near the n contact. The establishment of such a symmetrical space charge depends upon the steady state requirement that the electron and hole lifetimes be equal. However, during departures from steady state these lifetimes can be unequal, resulting in distortion of the space charge distribution within the i-region.

In Au-doped Si with the mid-gap acceptor level essentially empty at equilibrium, the electron lifetime is approximately $\tau_n = (c_n N_{Au})^{-1}$, where c_n is the electron capture coefficient and N_{Au} is the density of Au atoms. Since the hole capture cross section is large for this recombination center, a hole is captured almost immediately after electron capture, and the hole and electron capture rates are substantially equal. However, the mean lifetime per hole may vary if an imbalance in the relative electron and hole densities occurs. For example, in Fig. 5(b), we assume the value of $(p - n)$ is momentarily greater on the left than it is at steady state, and correspondingly $(n - p)$ to the right is smaller. In effect, the positive space charge has increased in the left-hand region and shifted into the right-hand region, moving the crossover $(p = n)$ point toward n. Since $(p - n)$ is larger on the left, the mean lifetime per hole is longer than it was at steady state. Thus more holes survive to neutralize the negative space charge on the n-side of the crossover point. Therefore, the effect of the recombination kinetics is to assist the movement of the space charge. On the other hand, the injected currents J_p and J_n oppose the space charge movement; in Fig. 5(b) J_p decreases as the positive space charge builds up near p, and J_n increases as the negative space charge is neutralized. By similar reasoning, a decrease in $(p - n)$ on the left-hand side of Fig. 5(c) results in a shorter hole lifetime and therefore a less complete neutralization of the negative space charge near n. Again, recombination assists the movement of the space charge. This imbalance results in a decrease in J_n and an increase in J_p. In this model the crossover point oscillates about the center of the i-region while the space charge builds up and relaxes alternately on the two sides. The injected hole and electron currents alternately rise and fall in response to the shifting space charge.

Although this model has not been worked out analytically, several observations can be made. As the experimental evidence suggests, the injected carrier density (and therefore $p - n$) must build up before any oscillating charge imbalance can be appreciable. Thus, a critical carrier density for oscillation is consistent with the model. The time required to build up and relax an imbalance in the carrier distribution should increase with injection, as $(p - n)$ increases. This agrees with the inverse dependence of frequency upon injected density (Fig. 4). Since a departure of $(p - n)$ from its steady state value relaxes by recombination with injected electrons and holes, the frequency should vary inversely with the average lifetime, as observed by Moore et al. Several important problems must be worked out in describing this model mathematically, including the role of the space charge due to altered occupancy of the Au centers. However, we believe that the basic mechanism indicated in Fig. 5 can serve as a starting point for further analysis.

Acknowledgments

We wish to thank M. M. Blouke, H. R. Zwicker, A. M. Andrews, G. E. Morris, and V. Swanson for technical assistance in this work.

References

1. N. Holonyak, Jr. and S. F. Bevacqua, *Appl. Phys. Letters* **2,** 71 (1963).
2. J. S. Moore, C. M. Penchina, N. Holonyak, Jr., M. D. Sirkis and T. Yamada, *J. Appl. Phys.* **37,** 2009 (1966).
3. J. S. Moore, N. Holonyak, Jr. and M. D. Sirkis, *Solid State Electronics* **10,** 823 (1967).
4. B. G. Streetman, M. M. Blouke and N. Holonyak, Jr., *Appl. Phys. Letters* **11,** 200 (1967).
5. M. M. Blouke, N. Holonyak, Jr., B. G. Streetman and H. R. Zwicker, to be published.
6. B. K. Ridley and R. G. Pratt, *J. Phys. Chem. Solids* **26,** 21 (1965).
7. S. G. Kalashnikov, M. S. Kagan, and V. A. Vdovenkov, *Soviet Phys.-Semiconductors* **1,** 88 (1967).
8. I. V. Karpova and S. G. Kalashnikov, *JETP Letters* **6,** 369 (1967).
9. M. Okuda and K. Yoshida, *Bull. Univ. of Osaka Prefecture* **16,** 225 (1967).
10. B. G. Streetman, H. V. Krone, N. Holonyak, Jr. and W. D. Compton, *Appl. Phys. Letters* **14,** 63 (1969).
11. W. Viehmann, *Appl. Phys. Letters* **14,** 39 (1969).
12. M. A. Lampert and A. Rose, *Phys. Rev.* **121,** 26 (1961).
13. N. Holonyak, Jr., *Proc. IRE* **50,** 2421 (1962).
14. For example, O. V. Konstantinov, V. I. Perel, and G. V. Tsarenkov, *Soviet Phys.-Solid State* **9,** 1381 (1967).
15. For example, V. L. Bonch-Bruevich and S. G. Kalashnikov, *Soviet Phys.-Solid State* **7,** 599 (1965).

Received April 8, 1969