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March 9, 1983

Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209

ATTENTION: Mr. Sven Roosild

SUBJECT: Quarterly Progress Report R920016-1 for Contract N00014-82-C-0697

Gentlemen:

We are pleased to enclose herewith the subject Report.

Very truly yours,

Harold L. Grubin
Vice-President
Solid State Device Research

HLG/jlh
Enclosure

cc: Distribution List (Attached)

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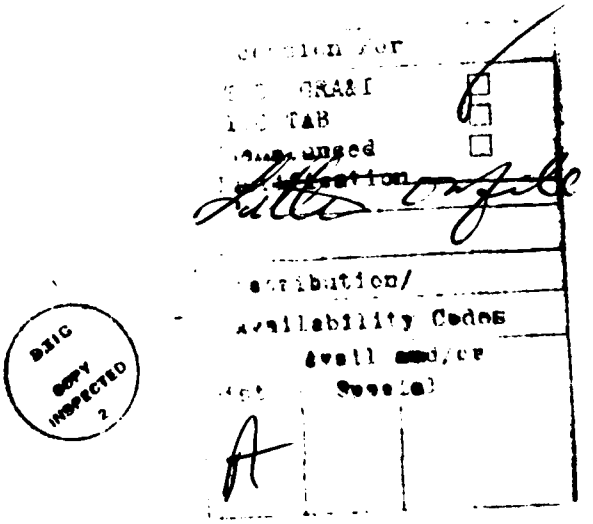

SEMICONDUCTOR MATERIALS FOR HIGH FREQUENCY SOLID STATE SOURCES

QUARTERLY REPORT: R920016-1

H. L. Grubin

March 1983

Defense Advanced Research Project Agency

ARPA ORDER NO: 4599 PROGRAM CODE NO.:

CONTRACT NO.: N00014-82-C-0697 CONTRACT AMOUNT: $179,790

EFFECTIVE DATE OF CONTRACT: 1 September 1982

EXPIRATION DATE OF CONTRACT: 31 August 1984

PRINCIPAL INVESTIGATOR: Dr. Harold L. Grubin

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SHORT TITLE OF WORK: Semiconducting Materials

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The broad goal of the subject contract is to suggest candidate materials for high frequency device operation. During the initial phase of the study, attention has been focused on defining the general role of the band structure and associated scattering processes in determining the response of semiconductors to transient high-speed electrical signals. Moments of the Boltzmann transport equation form the basis of the study, and the scattering rates define the semiconductor under study. Under uniform field conditions, and for multivalley semiconductors, these moment equations are

(particle conservation)

$$\frac{a_i \partial n_i}{\partial t} = \frac{-n_i}{\tau_{n_i}} + \frac{n_j}{\tau_{n_j}} \tag{1}$$

(momentum balance)

$$\frac{\partial n_i \vec{p}_i}{\partial t} = -en_i\vec{F} - \frac{n_i \vec{P}_i}{\tau_{pi}} \tag{2}$$

(energy balance)

$$\frac{\partial}{\partial t}\left(\frac{n_i p_i^2}{2} + \frac{3}{2} n_i k_o T_i\right) = -\frac{en_i \vec{F}\cdot\vec{p}_i}{m_i} - \frac{3}{2}\frac{n_i k_o T_i}{\tau_{E_i}} + \frac{3}{2}\frac{n_j k_o T_j}{\tau_{i_j}} \tag{3}$$

where the subscripts 'i' denote a particular section of the semiconductor, and the symbols n_i, p_i and T_i denote carrier density, momentum and electron temperature.

The selection of semiconductor materials proceeds from a set of simple, yet significant, set of scaling principles. During the first quarter scaling was associated with what can formally be identified as velocity invariants, but which in more practical terms identifies the relative speed advantages of e.g., InP over GaAs. We illustrate this below.

The velocity invariant has the following significance: In steady state, all time derivatives are zero, and the steady state velocity field curve for electrons has the form

$$v = -e\left(\sum -\frac{\tau_{pi}}{m_i}\right)F \tag{4}$$

where the sum is over the relevant sections of the conduction band. If the scattering rates (e.g., $\frac{1}{\tau_{pi}}$) were doubled, and the field across the device was doubled, the new velocity plotted against 2F, would bear the following relation to the old

$$V_{new}\left(2F, \frac{\tau}{2}\right) = V_{old}(F, \tau) \tag{5}$$

Further, if velocity transients were considered

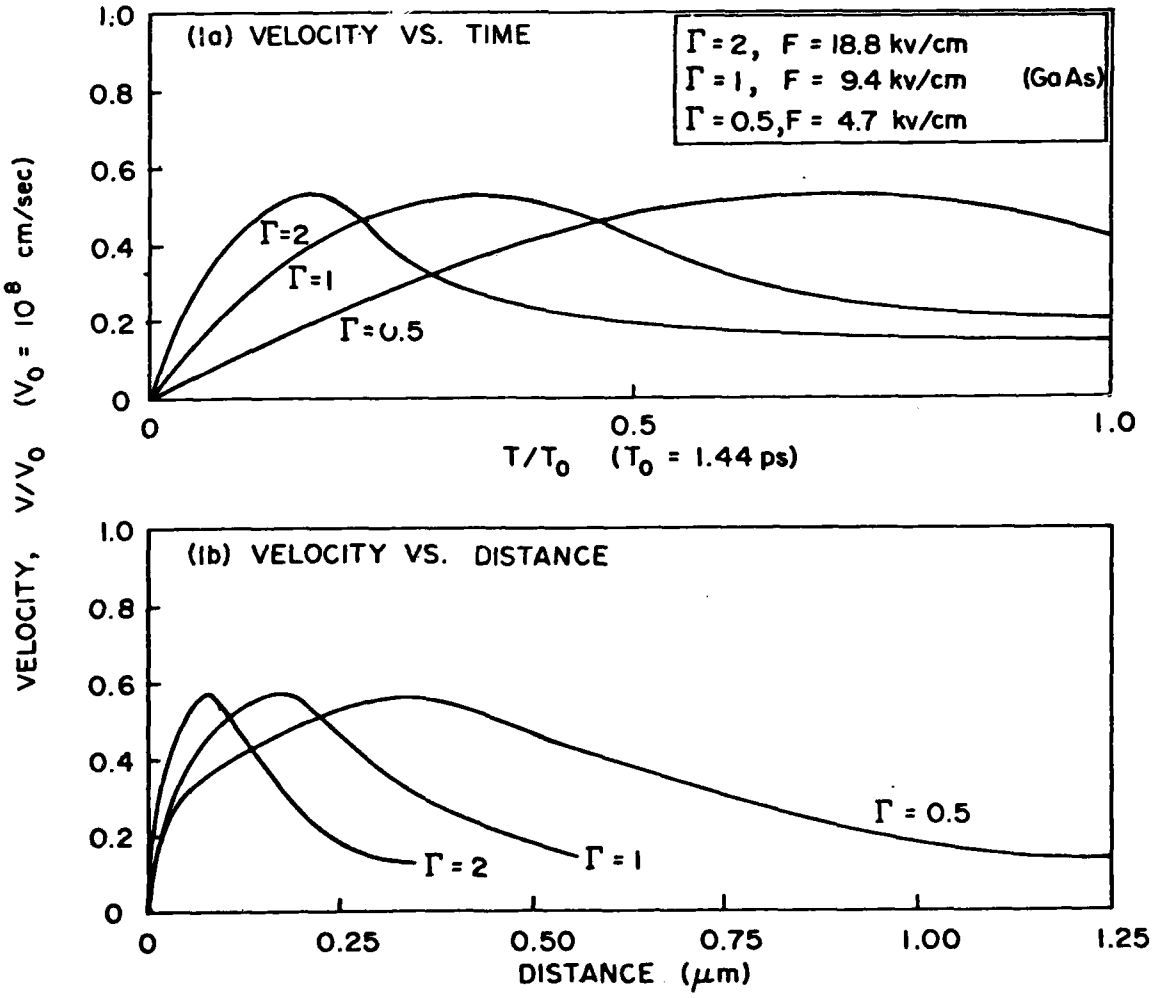
$$V_{new}\left(2F, \frac{\tau}{2}, \frac{t}{2}\right) = V_{old}\,(F, \tau, t). \tag{6}$$

The integrated distance

$$d = \int V dt \tag{7}$$

is similarly scaled.

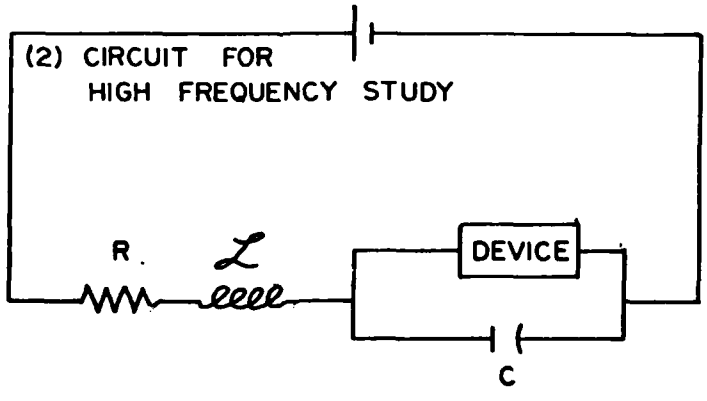
The above concepts have been utilized in interpreting results from recent numerical solutions to a scaled Boltzmann transport equation. In each of these calculations, the material of reference is gallium arsenide with electron transfer between the Γ, L and X portions of the conduction band. The first result shows the time dependence of the velocity subject to a sudden change in field, for GaAs (Γ = 1 scaling), and two other scaled materials (see Figure 1 where Γ denotes whether the scaling is doubled or halved.)

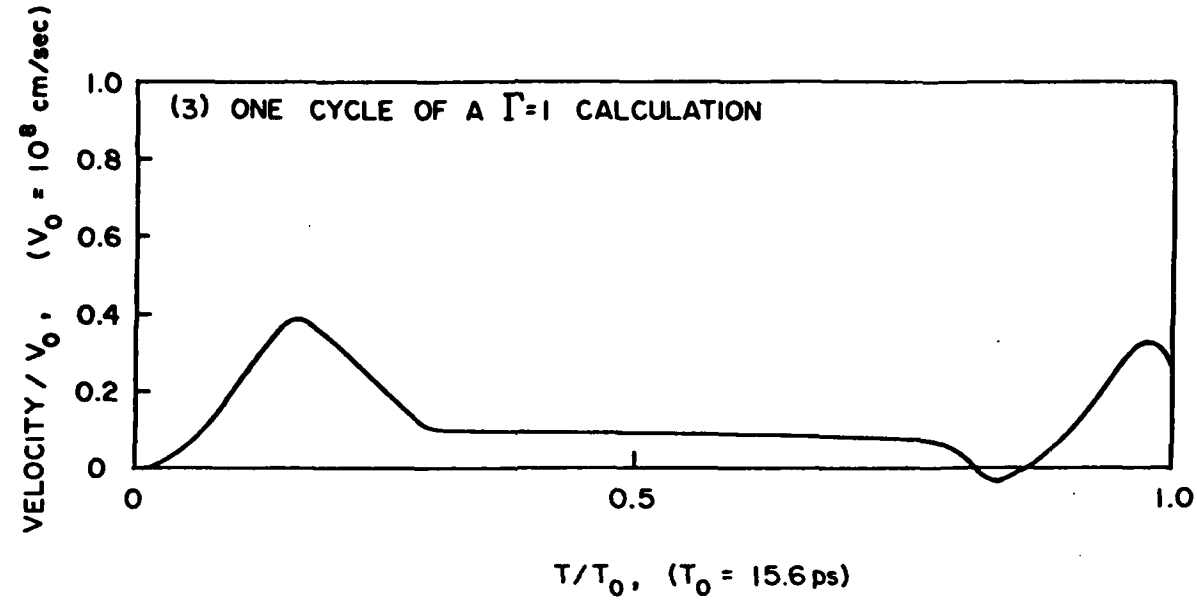


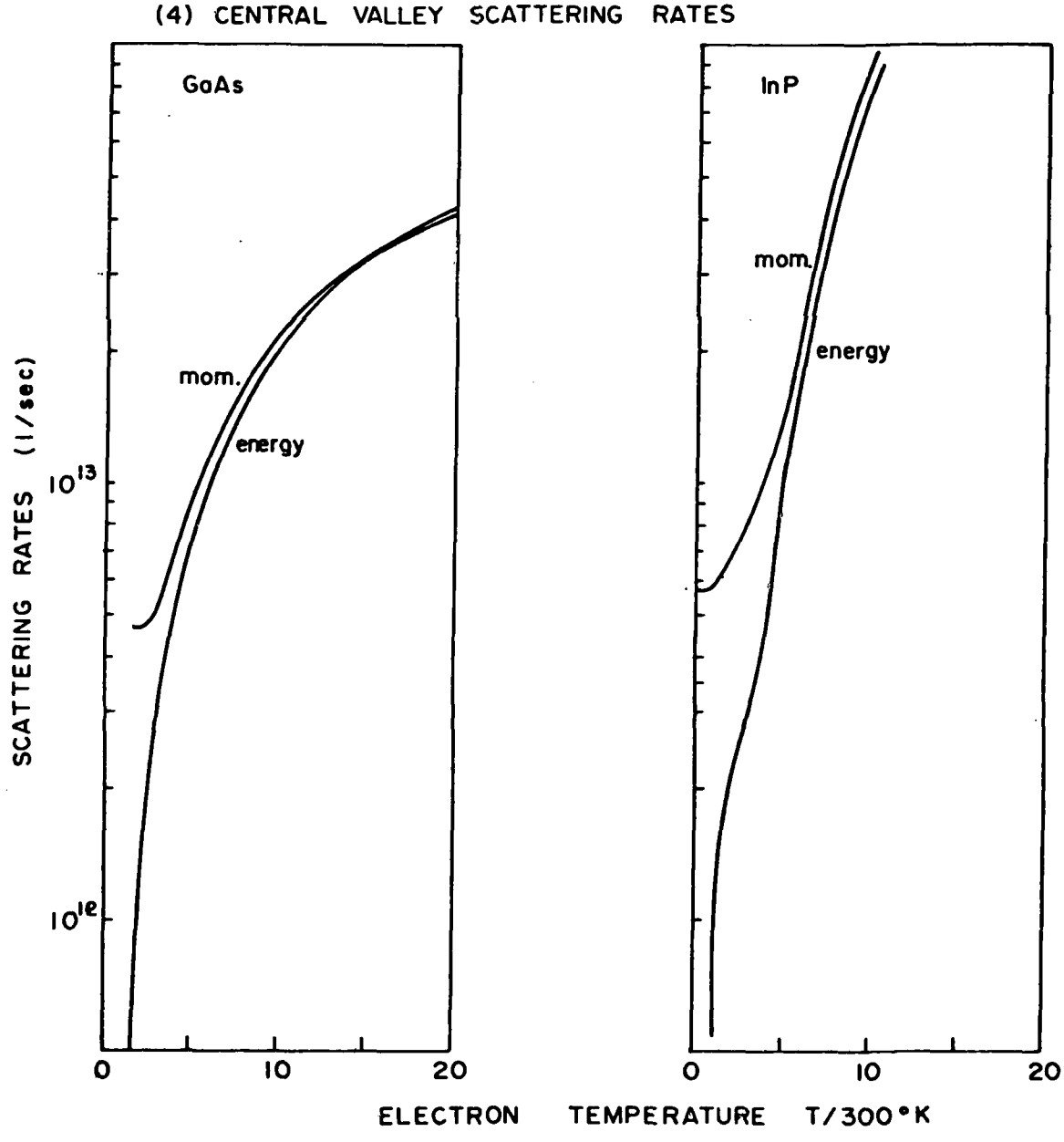
Figures 1a and 1b represent the transient response of gallium arsenide and two scaled elements. The scaled curve for $\Gamma = 2$ shows a more rapid response at higher bias levels and represents the consequences of increased scattering rates. While increased response times also occur, e.g., at increased bias levels for a given semiconductor, the significance here is the suggestion that the minimum response time for the higher Γ material is half that of the $\Gamma = 1$ GaAs material.

The above considerations arise simply from the Boltzmann transport equation. The effects of Poisson's equation and the external circuit have not been considered. The first test of the response time for the scaled elements was in the circuit of Figure 2, which when applied to gallium arsenide, yields maximum self-excited oscillation frequencies of approximately 130 GHZ. Figure 3 displays the time-dependent velocity for an approximately 78 GHZ self-excited oscillation. Scaling, to the higher Γ element, required an increase in donor doping. The scaled device sustained an oscillation frequency of approximately 150 GHZ, indicating that scaling can lead to higher frequency devices.

To place these scaling concepts in the context of two common semiconductors, Figure 4 displays the scattering rates for Γ valley momentum and energy scattering for GaAs and InP. The horizontal axis is the carrier temperature. We note that InP has higher scattering rates. We also point out that a cooling of the semiconductor reduces the net electron-phonon interaction, and the concomitant scattering rates. As a result, these scaling principles should again apply here.




(3) ONE CYCLE OF A Γ=1 CALCULATION
VELOCITY / V_0 , (V_0 = 10^8 cm/sec)
1.0
0.8
0.6
0.4
0.2
0
0
0.5
1.0
T/T_0 , (T_0 = 15.6 ps)


(4) CENTRAL VALLEY SCATTERING RATES
GaAs
InP
mom.
energy
mom.
energy
SCATTERING RATES (1/sec)
10^{13}
10^{12}
0
10
20
0
10
20
ELECTRON TEMPERATURE T/300°K