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PORT DATE

February 1993

3. REPORT TYPE AND DATES COVERED

FINAL REPORT Dec. 1989 to Dec. 1992

4. TITLE AND SUBTITLE

A Novel Approach for New Radiation Sources
Based on Solid State Plasma Instabilities.

5. FUNDING NUMBERS

DAAL03-90-G-0015

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8. PERFORMING ORGANIZATION
REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING
AGENCY REPORT NUMBER

AR0 26682.12-PH

11. SUPPLEMENTARY NOTES

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

In this program we have developed a Novel Approach for New Radiation Sources based on current driven plasma instabilities (CDPI) in layered solid state systems. We have demonstrated the feasibility of generating CDPI in a variety of systems, and of conversion of the energy of the growing plasma waves to electromagnetic radiation. We have identified the most promising candidates for experimental verification and device applications within the class of uniform lower dimensional systems. In addition, we have preliminary indications that modulated lower dimensional systems would significantly enhance these effects. We have also stimulated experimental efforts to confirm the results of our investigations.

93 5 04 06 3

93-09507



11p8

14. SUBJECT TERMS Current Driven Plasma Instabilities, Lower Dimensional Solid State Systems, Superconducting Layers, Ballistic Motion, Superlattices, Quantum Wires, Grating Couplers, Millimeter and Submillimeter Waves, Device Applications, Emission of Radiation

15. NUMBER OF PAGES
9

16. PRICE CODE

17. SECURITY CLASSIFICATION
OF REPORT

UNCLASSIFIED

18. SECURITY CLASSIFICATION

UNCLASSIFIED

19. SECURITY CLASSIFICATION
OF ABSTRACT

UNCLASSIFIED

20. LIMITATION OF ABSTRACT

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Final Report

**U.S. Army Research Office
Grant number: DAAL03-90-G-0015**

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I. Introduction

In this program we have developed a Novel Approach for New Radiation Sources based on current driven plasma instabilities (CDPI) in layered solid state systems. We have demonstrated the feasibility of generating CDPI in a variety of systems, and of conversion of the energy of the growing plasma waves to electromagnetic radiation. We have identified the most promising candidates for experimental verification and device applications within the class of uniform lower dimensional systems. In addition, we have preliminary indications that modulated lower dimensional systems would significantly enhance these effects. We have also stimulated experimental efforts to confirm the results of our investigations.

Section II provides a statement of the problem studied, section III summarizes the most important results and the last section lists all publications, and participating scientific personnel.

II. Statement of the Problem

The basic problem investigated in this program was a study of CDPI in solid state systems, leading to a novel approach for generation or amplification of electromagnetic radiation in the millimeter and submillimeter ranges, with potential applications to a new class of devices.

The basic principle is to utilize the energy of a dc current passing through a plasma, which leads to a plasma-instability. The instability mechanism transfers the energy from the current to characteristic plasma waves which grow in amplitude. These waves, in turn, can radiatively decay under an appropriate set up, emitting electromagnetic radiation in a predictable frequency range.

In this program we chose high mobility, lower dimensional, uniform systems as the solid state media for achieving CDPI, since they offer reduced carrier scattering effects and high carrier drift velocities.

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Our goal was to identify systems where the most efficient energy transfer from the current into the plasma waves occurs with the smallest possible drift velocities, and where a subsequent efficient conversion of this energy into electromagnetic radiation takes place.

III. Main Results.

We had investigated the feasibility of current driven instabilities in type I and type II semiconductor superlattices¹⁻³. The electron-phonon and electron-electron collisions were included through velocity independent collision rates. The carrier layers were taken to be strictly two dimensional (2D). For the *type II superlattice* (periodic arrangement of the type II heterojunctions), at liquid helium temperatures, we found¹ that a current driven instability occurs at a drift velocity of the order of the electron Fermi velocity. The amplifiable mode is an acoustic one, which without the driving current is not observable, since it is located in the single particle absorption continuum. Frequencies corresponding to the submillimeter-wave range can be generated. Even for the liquid nitrogen temperatures this instability can be generated with slightly higher drift velocities³. For the *type I superlattice*, we found² that a new, current-induced acoustic mode comes into existence at high drifts. It can be amplified at achievable drift velocities for liquid helium temperatures. Again, frequencies corresponding to the submillimeter- wave range can be generated. Single heterojunction of type I, as compared to the superlattice arrangement, yields the same threshold drift velocity, but a lower frequency range. The physical mechanism for the instability in all these cases is the inverse Landau damping.

Upon relaxing the assumption of the strictly 2D configuration of the charge carrier layers, the *finite layer size* creates multiple subbands. We found⁴ that, if only a single subband is occupied (in the driftless condition) in such a multisubband system, our previous results based on the strictly 2D layer model are recovered. If higher subbands are occupied (in the driftless condition), the threshold drift velocity for instability is reduced

due to the lowering of the Fermi velocity. We have also investigated the role of dimensionality by studying *quantum wire systems* (1D)⁵.

In addition, some novel systems were considered. Starting from the premise that the effects of collisions can be by-passed in superconductors, we had investigated current driven instabilities in *superconductor systems*⁶ at liquid helium temperatures. We found that another type of instability (so called beam-plasma instability) occurs by passing opposite currents in alternate layers. This instability does not require any threshold drift. A recent experiment provides a preliminary indication of transfer of energy from the driving current into the carrier plasma in broad agreement with our theory⁷. The effects of collisions can also be avoided in the *ballistic motion* of electrons. Streams of such electrons, with extremely high velocities, can now be experimentally achieved. We found⁸ that instability is indeed possible and the physical mechanism is the inverse Landau damping. Frequencies corresponding to the submillimeter-wave range can be generated. In a somewhat different context we had noted that instabilities in the quantum resonance devices⁹ (e.g. quantum resonant diodes) can also be viewed as current driven plasma instabilities.

In May 1991 the Army Research Office hosted a "Workshop on Solid State Amplification Schemes for Electromagnetic Waves in the MMW/SMMW Region". Presentation of the results of our program and the ensuing discussions were a major part of this workshop. There was considerable interest in the gain levels of current driven plasma instabilities that could be achieved in realistic systems (we presented a preliminary account on this subject at the Workshop). Another important issue was whether the plasma waves could be efficiently coupled to electromagnetic radiation.

Since then we completed our study of the growth rates of current driven plasma instabilities, and showed¹⁰ that significant gains can be achieved in a variety of layered systems. We also developed a theory for the combined system of a grating coupler and the layered system which generates the instability, obtaining quantitatively for the systems

studied the efficiency for conversion of the plasma wave energy into the electromagnetic radiation¹¹. We also discovered that the grating can play an active role in *generating* a new instability, which is similar to the resistive wall instability.

In addition, we have stimulated efforts towards experimental verification of these phenomena. A recent experiment here (at Boston College) based on our ideas offers a preliminary confirmation⁷. It shows the occurrence of a drag between two layers of superconducting carriers (one of them moving). This drag could be due to a rapid dissipation of energy of carriers through spontaneous generation of plasmons. The energetic analysis of this system is in broad quantitative agreement with our theory. Efforts are also under way at Princeton University to obtain experimental verification in semiconductor-based systems¹².

We have also studied¹³⁻¹⁷ novel lower dimensional systems (quantum wires and dots) for possible application as grating couplers which might offer special advantages. In contrast to the conventional metallic strip grating, a quantum wire (or dot) grating has its own characteristic frequency of oscillations, in the frequency domain of our interest. Resonant interactions will occur when this characteristic frequency matches the frequency of the current driven plasma mode in the layered system beneath the wire array, and q , the momentum of the plasmon, matches the grating period. These interactions allow for direct coupling of the system to the electromagnetic radiation. A spontaneous emission of photons will occur due to the transition back from the excited state to the ground state.

In conclusion, we have now shown theoretically for various layered solid state systems that current driven plasma instabilities can be generated, plasma waves can grow and the energy can be radiated in the millimeter/submillimeter wave range. We find that the most promising semiconductor media are systems in the ballistic mode of operation^{8,10}. In a high mobility sample, this scatteringless environment is possible as long as the distance between electrodes is less than the mean free path $L \sim 100 \mu\text{m}$. As a typical example, if the density of ballistic and stationary electrons is $n_s = n_b = 10^{11} \text{cm}^{-2}$, the threshold velocity is $\sim$

2.5x10⁷cm/s. This threshold drift can be lowered in two ways: by lowering the density and by considering a counter-streaming ballistic arrangement, where the two layers drift in opposite directions with equal velocities. For $n=2 \times 10^{10} \text{cm}^{-2}$, in such a counter-streaming ballistic arrangement, we only need 0.5x10⁷cm/s as a threshold drift and even 1.0x10⁷cm/s provides a growth rate of 1.4x10¹²s⁻¹, which corresponds to an e-folding distance of a few hundred Å. This extremely strong instability allows an amplification of several orders of magnitude, even for a 10μm range of ballistic operation. For a typical value¹⁰ of the plasma wave number 4x10⁵ cm⁻¹, the grating period to quench the momentum is about 1600Å. The corresponding frequency is greater than 2x10¹² s⁻¹, and the wavelength of the emitted radiation is in the millimeter to submillimeter regime. Typical amplitude conversion efficiency of the standard metallic strip grating¹¹ is about 1%. Additional feedback mechanisms through a surrounding resonant cavity can further enhance the efficiency.

The threshold drifts in the non-ballistic mode of operation are higher and, while still achievable within the current state of the art technology, pose a practical problem. Our cumulative experience on this program leads us to suggest that ultimately the best systems could be the modulated lower dimensional systems. They can offer a twofold advantage: the threshold drift velocities are significantly lowered, and the modulation acts as a built-in grating. Our recently initiated preliminary studies confirm this.

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IV. Publications and Personnel.

a) Publications

1. P. Bakshi, J. Cen and K. Kempa, " Current driven plasma instability in quantum wires", Solid State Communications 76, 835-837, (1990).
2. P. Bakshi, D.A. Broido and K. Kempa, " Electromagnetic response of quantum dots", Phys. Rev. B42, 7416, (1990).
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b) Personnel

1. P. Bakshi (Faculty), Principal Investigator
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J. Cen, Ph.D., Boston College, 1991

Thesis title: "Current driven plasma instabilities in layered solid state systems"

d) Reportable inventions.

None