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THEORY OF CYCLOTRON RESONANCE AT INTENSE MICROWAVE FIELDS

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A carrier strongly interacting with the optical phonon undergoes a streaming cyclotron motion in intense microwave fields; it is repeatedly accelerated up to the optical phonon energy within a half cycle of the field. Some peculiar properties of the motion, such as the bunching of the carriers in the momentum space, are described. Sequential change of the distribution function is explicitly presented.

In many semiconductors, the carrier strongly interacts with the optical phonon. When the crystal is good and the temperature is low, the collision time of the carrier is long if the energy ε is less than the optical phonon energy $\hbar\omega_{op}$, while it is short if $\varepsilon>\hbar\omega_{op}$ because of the optical phonon emission. If suitably strong electric field is applied, the carrier is accelerated rather freely from low energy region to $\hbar\omega_{op}$ then immediately emits an optical phonon and returns to the low energy region. Such a motion is often called the "*streaming motion*" [1].

Similarly, a phenomenon to be called "*streaming cyclotron motion*" is expected in crossed magnetic and sufficiently strong microwave fields, where the carrier is repeatedly accelerated up to the optical phonon energy within a half cycle of the microwave field; the situation is completely different from the usual cyclotron resonance condition.* We have reported some evidences of the streaming cyclotron motion in AgBr at the Edinburgh Conference [2]. A rapid increase of the line width and a pronounced peak shift with the microwave intensity have been observed. A Monte Carlo calculation has reproduced the experimental results very well and also supported the concept of the streaming cyclotron motion.

Furthermore, the calculation discloses several interesting features which have not been found experimentally: The streaming cyclotron motion shows generally very systematic patterns rather than an erratic behaviour expected from the brutal acceleration. The peculiar characters of the motion are most clearly demonstrated by examining

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* The *streaming cyclotron motion* should be distinguished from a situation to be called "*streaming cyclotron resonance*", in which the condition $(eE_0\tau)^2/2m^*>\hbar\omega_{op}$ is satisfied and the carrier is accelerated up to $\hbar\omega_{op}$ after several cycles of the field if $\omega\simeq\omega_c$. (E_0 and ω are the amplitude and the angular frequency of the microwave field and τ the average collision time of the carrier with $\varepsilon<\hbar\omega_{op}$.) On the other hand, the condition $(eE_0/\omega)^2/2m^*>\hbar\omega_{op}$ is required in the case of the streaming cyclotron motion.

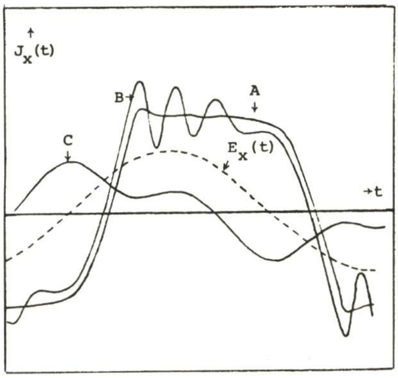

Fig.(1) The calculated current response J_x to the microwave field as shown by the dotted line
(A) E_0=960V/cm ω_c=0
(B) E_0=960V/cm ω_c/ω=0.6
(C) E_0=780V/cm ω_c/ω=3

the calculated current response $J_x(t)$ to the microwave field $E_x(t)=E_0\cos\omega t$. Figure (1) shows $J_x(t)$ for various cases, where ω_c is the cyclotron frequency and $\omega/2\pi$ is taken to be 35GHz.* The sawtooth current in the case B and the strong third harmonic generation in the case C are remarkable.

The first effect is ascribed to the carrier bunching in the p-space, the peak of the current corresponds to the moment of the arrival of the bunched carriers at the optical phonon energy. The origin of the bunching is explained as follows: If we follow the repetition of such an idealized motion that a carrier is accelerated from p=0 to $\hbar\omega_{op}$ and returns to p=0 again under crossed microwave and magnetic fields of appropriate strengths, we find that the motion converges to a particular limiting motion (*limit cycle*) irrespective of the initial condition. In other words, the phase of $E_x(t)$ at which the carrier arrives at the optical phonon energy converges to some constants which depend on E_0/ω and ω_c/ω. Sometimes the convergence is very rapid; when $\omega_c/\omega=0.4\sim0.8$ for instance, only a half cycle is sufficient to give a practical convergence. As a matter of fact, the convergence is more or less disturbed by the scattering of carriers with energy $\varepsilon<\hbar\omega_{op}$ and the widespread carrier distribution around p=0 after the optical phonon emission.

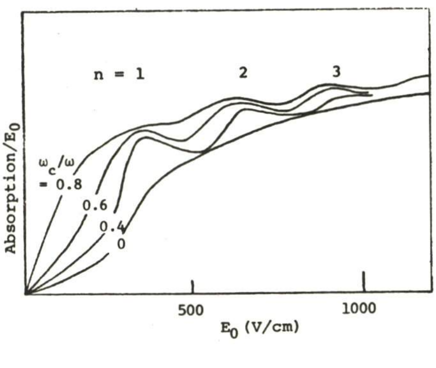

Fig.(2) The stepwise increases of the microwave power absorption

The number of optical phonons emitted during a half cycle by a carrier moving along the limit cycle is generally an integer. The integer n is proportional in a general trend to E_0 but increases rather abruptly by 1 across a narrow transition region of E_0, where *e.g.* two limit cycles coexist. This reflects the stability of the limit cycle. In the present situation, the optical phonon emission is the dominant dissipation process and detdermines the power absorption. Thus we can expect that the absorption for $\omega_c/\omega=0.4\sim0.8$ is roughly proportional to E_0 but exhibits stepwise increases. The calculation confirms this expectation as shown by Fig.(2), where the ordinate is taken to be absorption/E_0 to emphasize the effect. When $\omega_c=0$, there is no appreciable anomaly.

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* All the calculations described here are carried out for AgBr, in which the polar-optical, acoustic and neutral impurity scattering processes are considered. The collision frequency by the impurity is fitted to give the experimentally observed low field mobility at 4.2K, 2×10^5 $cm^2/V\cdot s$.

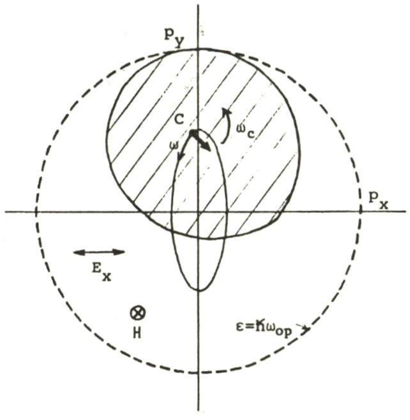

Fig.(3) The explanation of higher harmonic generation; the accumulation of carriers in the p-space is shown by hatching. The point C moves on the ellipse, while the hatched region rotates around C

The higher harmonic generation is caused by a coherent circular motion of the carriers accumulated in the region as hatched in Fig.(3), rotating with ω_c: The free motion of a carrier in the p-space is given by a sum of the elliptic motion driven by the microwave field and a circular motion of ω_c. If E_0/ω_c is not too large, the ellipse does not reach the optical phonon energy and there is the region that the energy of a carrier in it never becomes $\hbar\omega_{op}$. The carriers accumulate in it, because the collision time is long there. If ω_c/ω is an odd integer (>1), the region has an assymmetric shape as shown in Fig.(3), which induces a dipole moment rotating with ω_c.

As seen above, the streaming cyclotron motion reveals various characteristic features depending on the parameters E_0/ω and ω_c/ω. These features reflect those of the distribution functions. Therefore it is of interest to see explicitly the sequential change of the distribution function during a half cycle. We present a number of slides for this purpose in the talk, but only a few typical examples here. Figures (4)-(11) shows the distribution functions on the $p_z=0$ plane. In the inset, the field E_x and the current J_x (sometimes also J_y) are plotted together with the indication of the corresponding time at which the distribution is recorded (the vertical arrows). Figures (4) and (5) show the case E_0=1200V/cm and $\omega_c=0$. Figures (6)-(8) are for E_0=1200V/cm and $\omega_c/\omega=0.8$, demonstrating the bunching effect. The case C in Fig.(1), E_0=780V/cm and $\omega_c/\omega=3$, is shown in Figs.(9)-(11), where the rotating dipole moment is indicated by the arrows.

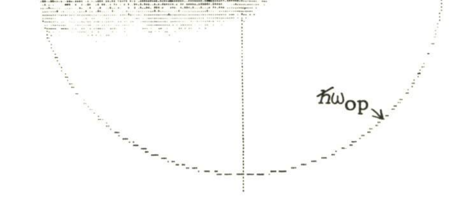

Fig.(4) E_0=1200V/cm

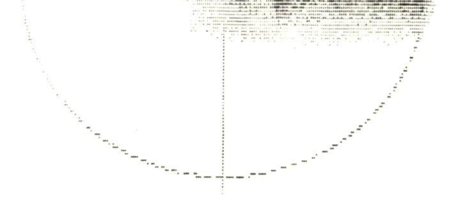

Fig.(5)

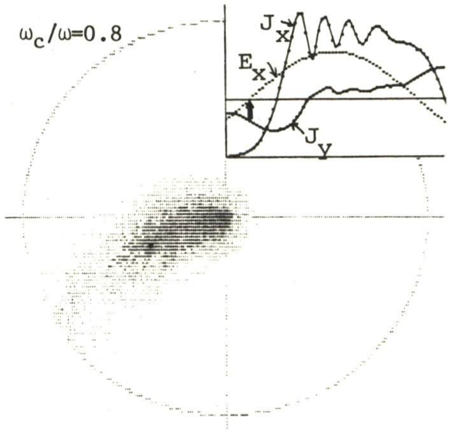

Fig.(6)

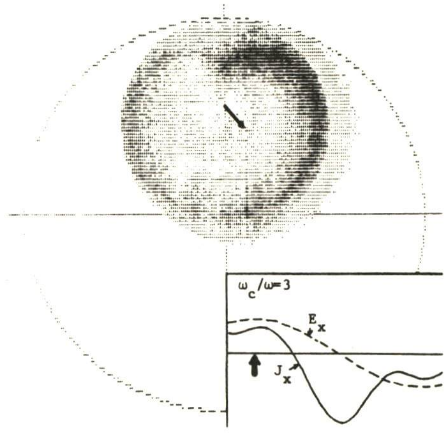

Fig.(9)

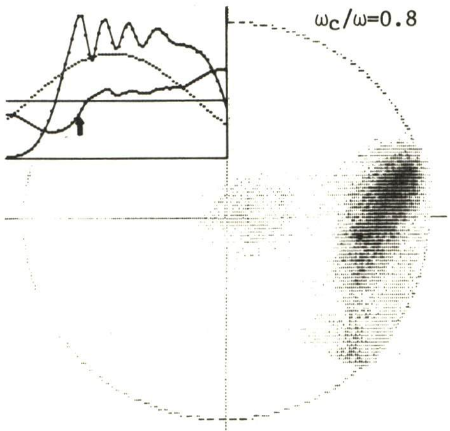

Fig.(7)

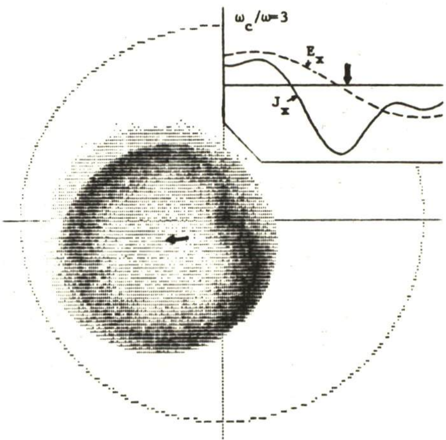

Fig.(10)

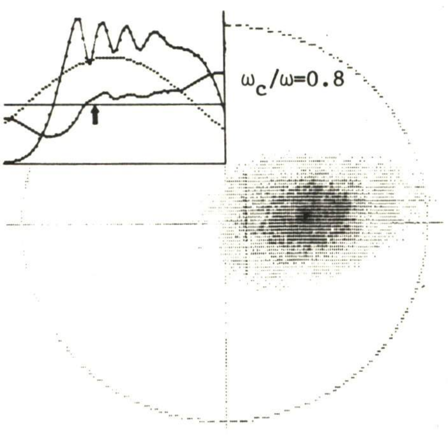

Fig.(8)

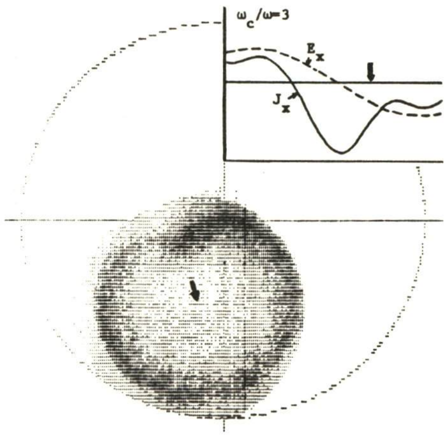

Fig.(11)

References

1) W.E. Pinson & R. Bray: Phys. Rev. 136 (1964) A1449.
2) S. Komiyama, T. Masumi & T. Kurosawa: *Proc. 14th Int. Conf. Phys. Semiconductors, Edinburgh* (1978) p.335.