



APPLIED
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T—Theoretical, E—Experimental, T/E—Theory supported by experiment.

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ELECTRON TUNNELING INTO AMORPHOUS GERMANIUM*

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(Received 30 September 1969; in final form 4 December 1969)



Al—Al₂O₃—Ge tunnel junctions were prepared to study electron tunneling into amorphous germanium films. An almost symmetric conductance minimum centered at zero bias without additional structure was observed. The change in conductance from 1 V to zero bias is 10³ at 78°K and about 10² at 300°K. The zero bias conductance is 10² times lower at 78°K than at 300°K. The results indicate a large density of states in the gap or near the surface.

Nwachuku and Kuhn¹ pointed out recently that information about the energy gap and the band tailing of amorphous semiconductors may be obtained by studying the tunneling current from a metal electrode through an oxide barrier to the amorphous semiconductor. Using amorphous Ge they indeed found a rather sharp increase in tunneling conductance at negative and positive bias values which were separated by approximately 1 V. This value agrees quite well with the energy gap determined from the temperature dependence of the electrical resistivity of amorphous Ge.² In addition they observed¹ some smaller structure in the bias dependence of the tunneling conductance which was tentatively interpreted as coming from gap states.

We repeated these experiments³ with great care. Our results differ significantly from those of the previous authors. The conductance curves do not yield the band gap of the amorphous material in a straightforward manner and no smaller structure was observed.

The Al—Al₂O₃—Ge tunnel junctions were prepared by evaporation onto glass substrates in an ion-pumped vacuum system at pressures between 10⁻⁶ and 10⁻⁷ Torr. The oxide was formed by plasma oxidation in 0.1 Torr of dry oxygen gas. The Ge was deposited at a rate of 50—100 Å/sec to thicknesses between 400 and 2000 Å. A layer of Al was deposited on top of the amorphous Ge in order to minimize the voltage drop in the Ge electrode. A layer of SiO was evaporated over the whole sample to protect it from moisture. A rotating sample holder and a sufficient number of sources made it possible to prepare the samples without opening the bell jar.

The quality of the oxide tunnel barrier and of the amorphous Ge was ascertained in the following manner. Five junctions were prepared simultaneously on the same pyrex substrate: three MOSM, one MOM, and one MSM junction (M stands for metal, O for oxide, and S for amorphous semiconductors).

By using Au as the bottom electrode, oxide for-

mation was avoided in the case of the MSM junctions. The resistance of the MSM junctions scaled with the germanium thickness. This indicates (i) that the contacts were not blocking and (ii) that there were no problems caused by metal bridges or pin holes. The magnitude and temperature dependence of the germanium resistivity agreed with that expected² for amorphous germanium deposited at the rate specified above. Even at 78°K the resistance of the MSM sandwich remained several orders of magnitude below that of the MOSM junctions so that in these the voltage drop occurs predominantly across the oxide tunnel barrier.

The MOM junctions served as a quality check and monitor of the oxide layer thickness. The MOM tunnel resistance was approximately 30 Ω and changed only slightly with temperature and bias. With the same oxide layer, the resistance of some MOSM tunnel junctions exceeded 10⁶ Ω at zero bias and low temperatures. Part of the observed increase in resistance is probably due to an increase in the tunneling barrier. Placing germanium instead of a metal electrode next to the insulator reduces the image charge of the tunneling electron. The major part of the difference in tunneling resistance between MOM and MOSM junctions must, however, be attributed to the role played by the amorphous semiconductor in the tunneling process because of the strong bias and temperature dependence observed in the latter case.

An attempt was made to determine the thickness beyond which the tunneling conductance becomes independent of germanium layer thickness. For this purpose germanium was deposited through a rotating sectioned shutter onto several Al—Al₂O₃ strips so that the germanium thickness was different for each strip. For the thickness determination, a quartz crystal thickness monitor and the density of crystalline germanium were used. The zero bias tunneling resistance rises rapidly and then becomes constant near 50 Å. Whether this value is a measure of the screening length in the semi-

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T-Theoretical, E-Experimental, T/E-Theory supported by experiment.

of the form

$$M_y = \exp[i(\omega_k t - \vec{k} \cdot \vec{r})] \sum_n a_n \cos[n(\Delta\omega_k t - \Delta\vec{k} \cdot \vec{r}) + \phi_n]. \quad (4)$$

The YIG disk with two parallel surfaces acts as a Fabry-Perot cavity for the spin waves, and many spin-wave modes are set up in the cavity. The difference in k between two neighboring modes is denoted in Eq. (4) by Δk and their difference in ω_k by $\Delta\omega_k$.

If Eq. (4) is indeed a correct description of spin waves in the instability experiment, then the interaction of two spin waves M_{y1} and M_{y2} in Eq. (1) should produce an acoustic wave having a fundamental frequency $\Delta\omega_k/2\pi$. This frequency should be the same as that of the low-frequency oscillation reported in Ref. 1. Figure 2 shows the electrical signal received at the transducer. There is a time delay between the initiation of the microwave power and the arrival of the acoustic wave at the transducer. The delay is a sum of the time required for the spin-wave instability to set in and the time required for the propagation of the acoustic wave in quartz. Measurements of the delay in several quartz rods of different lengths yields an acoustic-propagation velocity of 6×10^5 cm/sec which is in agreement with the longitudinal velocity of 5.986×10^5 cm/sec reported in fused quartz.⁷

The observation of the parametric excitation of low-frequency acoustic waves supports our contention advanced in Ref. 1 that the observed low-frequency oscillation is caused by the time variation of the spin-wave modes. It also led us to a subsequent experiment. Eliminating M_x from Eqs. (2)

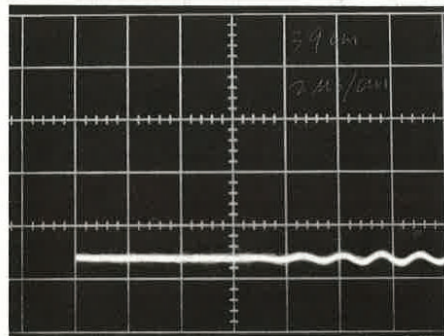


FIG. 2. Oscilloscope trace showing the electrical output at the transducer. The signal is caused by acoustic waves parametrically generated by two spin-wave modes. Horizontal scale: $2 \mu\text{sec/division}$.

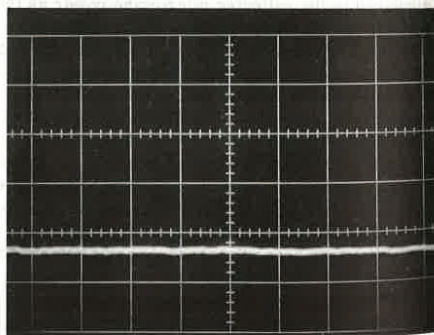
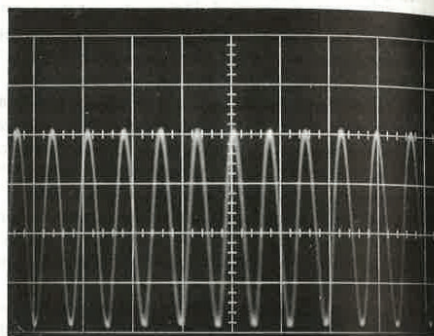
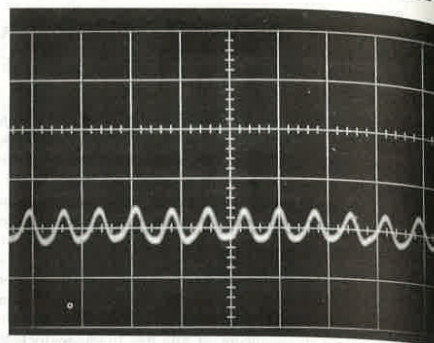


FIG. 3. Oscilloscope traces showing the low-frequency modulation of the reflected power in the mode-locking experiment. Pictures (a) and (b) were taken in the subsidiary-absorption region of spin-wave instability: (a) without incident acoustic wave and (b) with incident acoustic wave. Picture (c) was taken at a dc magnetic field 150 Oe above the region for subsidiary absorption with incident acoustic wave. Horizontal scale: $2 \mu\text{sec/division}$.

and (3), we have

$$\frac{\partial^2 M_y}{\partial t^2} = -\omega_k^2 M_y - (A_k + B_k) \frac{2\gamma B_1}{M_s} \frac{\partial R_y}{\partial y} M_y. \quad (5)$$

If a low-frequency acoustic wave is sent through the quartz rod, the acoustic wave may phase-lock two neighboring spin-wave modes through the $\partial R_y / \partial y$ term in Eq. (5). The mode-locking effect should be strongest when the angular frequency of the acoustic wave is equal to $\Delta\omega_k$. This is indeed the case.

Figure 3 shows the low-frequency oscillation of the reflected microwave power: (a) without the acoustic wave, and (b) with the acoustic wave. The enhancement of the amplitude of the modulation is a result of phase-locking of the many spin-wave modes. To ensure that the observed effect is due to parametric coupling of spin waves through the magneto-elastic effect and not due to unforeseen elastic effect alone, we changed the dc magnetic field to regions outside the range for subsidiary absorption. As shown in Fig. 3(c), no low-frequency oscillation was observed. Insofar as we are aware, this is the first experiment on mode-locking of spin waves. Of course, mode-locking of laser beams has been investigated extensively.⁸

In many investigations and applications involving spin waves, one difficulty we face is that the spin-wave amplitude is low because there are so many spin-wave modes. One example is the spin-wave light-diffraction experiment. The positive results reported here offer some hope that mode-locking may be the answer to enhance the spin-wave am-

plitude. The effect of mode-locking on spin waves reported here is not as pronounced as the effect of mode-locking on laser beams. The main reasons for the comparatively small effect are as follows. There are fewer than ten spin-wave modes under the experimental condition described above. The effect of dispersion on mode-locking is expected to be more severe for spin waves than for light beams. Spin-spin relaxation also may limit the effect of mode-locking.

We would like to thank Professor C. W. Turner for many helpful discussions.

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¹S. Wang, C. Thomas, and Ta-lin Hsu, *J. Appl. Phys.* **39**, 2719 (1968).

²T. S. Hartwick, E. R. Peressini, and M. T. Weiss, *J. Appl. Phys.* **32**, 2238 (1961).

³G. E. Bodway and S. Wang, *J. Appl. Phys.* **36**, 2566 (1965).

⁴C. Kittel, *Phys. Rev.* **31**, 1647 (1960).

⁵See, for example, R. L. Comstock and B. A. Auld, *J. Appl. Phys.* **34**, 1461 (1963).

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⁸See, for example, M. DiDomenico, *J. Appl. Phys.* **35**, 2870 (1964); V. S. Letokhov and V. N. Morozov, *Soviet Phys. JETP* **25**, 862 (1967); H. Statz and M. Bass, *J. Appl. Phys.* **40**, 377 (1969); A. Yariv, *Quantum Electronics* (John Wiley & Sons, Inc., New York, 1967).

LASER-GENERATED STRESS WAVES*

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(Received 10 November 1969)

A method of generating stress waves with a laser is demonstrated using a transparent material to impede the expansion of the vaporized absorber. A stress wave whose magnitude is 34 kbar and whose width at half-maximum is equal to the width of the laser pulse is reported.

Several publications have dealt with the creation of stress waves using lasers.¹⁻¹² The use of a transparent material and thin-film absorber has been reported previously.¹³ This letter reports accurate stress measurements in the immediate vicinity of the absorber and the time history of the stress wave. Experiments on the symmetry of the resulting stress wave are also reported.

A schematic of the experimental configuration is shown in Fig. 1. The laser used was Korad

K1500 oscillator-amplifier ruby system. The nominal parameters were 7 J in 12 nsec. The absorber was located in a vacuum chamber 6 ft from the output end of the amplifier. The radiation was focused by a simple lens, of 38 mm focal length, through a quartz disk, 6 mm thick, into a circular region, 6 mm in diameter, on an aluminum film vapor deposited to the back of the quartz disk. The aluminum film, which had been previously deposited, was 0.5 μ thick. To the back of the

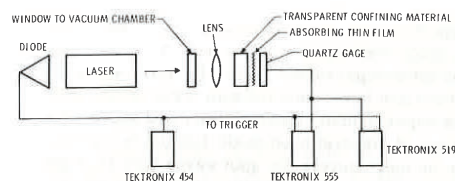


FIG. 1. Schematic of the experimental configuration.

aluminum film, a thick quartz gage¹⁴ was epoxy bonded. The output from the quartz gage was recorded on a Tektronix 519 oscilloscope, to measure its time development, and on a Tektronix 555 to provide an accurate amplitude measurement. A second experiment was performed where the quartz gage was replaced by a second quartz disk. No active measurements were made as the purpose was to demonstrate that the magnitude of the stress propagated away from the laser was essentially of the same magnitude as that propagated toward the laser. By observing the damage in the two quartz disks, an assessment is made of the symmetry of the stress wave propagation into the two confining quartz disks.

The quartz gage that was used in these experiments was 9.55 mm in diameter, 1.27 mm thick, and had a guard ring diameter of 3.81 mm. The sensitivity of this gage is 0.59 V/kbar when the gage is used with a 50-Ω load. The output of the gage as recorded by the Tektronix 519 is shown in Fig. 2(b). Figure 2(c) is a reproduction of the trace from the Tektronix 555 and Fig. 2(a) is the recorded laser pulse. The rise time of the stress wave is nominally the laser pulse width. The peak amplitude indicates a pressure of 34×10^9 dyn/cm² (34 kbar) in the quartz. In the case where the quartz gage is replaced with a quartz disk similar to the disk with the aluminum film and care is

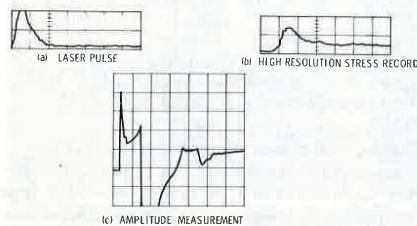


FIG. 2. (a) Reproduction of oscillograph of laser pulse horizontal scale 20 nsec/div. (b) Reproduction of oscillograph from 519 recording of stress wave time history: horizontal scale 20 nsec/div. (c) Reproduction of oscillograph from 555 recording of amplitude of stress wave: horizontal scale 0.2 μsec/div; vertical scale 5 V/div.

taken to insure that the debris from each disk is kept separate, it is found that the damage caused by the stress wave is symmetrical with respect to the absorber. This damage observed is, in a general way, very similar from test to test. A volume near the absorber appears crushed but is in one piece. The material surrounding this is crushed to a fine powder and scattered. The outer regions are broken into large pieces but are otherwise undamaged. There is no evidence of any laser deposition in the quartz between the absorber and the laser. The laser energy transmitted by the absorber has been measured independently to be less than 10^{-4} of the incident energy. The laser energy reflected by the absorber has been measured with the same photodiode and Tektronix 519 oscilloscope as the incident pulse. It was found that less than 10% of the incident energy is reflected. The stress record reported here should be compared to the results of Palmer and Asmus¹⁵ who studied the effect of ambient gas on the stress produced by laser radiation on a free metallic surface. The time history they report for a gas pressure of 0.06 Torr is similar to Fig. 2(b).

If the absorber is treated as a perfect gas bounded by material with an acoustic impedance Z , it is found that the maximum pressure developed is¹⁶

$$P_{\max} = (ZE_0/3t_D)^{1/2},$$

where E_0 is the fluence in erg/cm² and t_D is the laser pulse width (taken here to be the full width at half-maximum). With the values

$$E_0 = 7.1 \text{ J}/0.31 \text{ cm}^2 = 22.8 \text{ J/cm}^2,$$

$$Z = \rho C_0 = 2.2 \text{ g/cm}^3 \times 6.0 \times 10^5 \text{ cm/sec},$$

(ρ is the density and C_0 the bulk sound velocity in quartz) and

$$t_D = 12 \times 10^{-9} \text{ sec},$$

a value is found of

$$P_{\max} = 29 \times 10^9 \text{ dyn/cm}^2.$$

The PdV work is estimated to be (from $P \times C_0 \times t_{\text{Dep}}$)

$$PdV = 2.1 \times 10^7 \text{ erg/cm}^2$$

and hence accounts for approximately 10% of the energy.

It is clear from the Saha equation, that for plasmas created by lasers,¹⁷⁻²³ a considerable degree of ionization is present, thereby accounting for a considerable percentage of the energy. Thus, the measured pressure appears to be in reasonable

agreement with these elementary (and approximate) considerations.

It has been shown that stress waves with a magnitude of 34 kbar can be created by using the confined blow-off concept together with a thin-film absorber. The time history of such waves has been recorded and it was found that the duration of the applied stress is comparable to the laser duration.

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SHOT NOISE IN JOSEPHSON POINT CONTACTS

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Experimental evidence is presented showing that the noise in Josephson point contacts is shot noise limited. Comparison with theory indicates that the pair current contribution is not as large as predicted.

Recently Dahm *et al.* demonstrated the noise properties of tunnel currents in thin film junctions from linewidth measurements on radiation emitted at the Josephson frequency.¹ We report the direct measurement of current fluctuations observed on weak link point contacts when operated as microwave detectors in a video-type receiver. Point contact junctions are suitable as detectors since their impedance can be made sufficiently large to allow reasonable matching to the radiation field. In this application the noise properties are of considerable practical importance.

Point contacts were made in liquid helium by pressing fine niobium wire tips against a flat niobium surface covered with an oxide layer formed

in air by heating to 80 °C for an hour. The contact mount was stable enough to substantially avoid disturbances by mechanical vibrations. The electronic circuit is sketched in Fig. 1(a). The sample was operated in series with a transformer which coupled the sample to a tuned amplifier whose output was recorded. The frequency of 120 kHz was high enough to insure operation beyond the roll off of a $1/f$ noise contribution² which was found to dominate at frequencies up to several tens of kHz. All meter and battery connections were filtered, the sample region shielded from magnetic field fluctuations by a superconducting shield, and the entire experiment conducted in an electromagnetically shielded room.