STIMULATED EMISSION OF RADIATION FROM GaAs p-n JUNCTIONS

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of the electrons in the conduction band would probably be trapped, and the resulting space charge would increase the height of the tunneling barrier.

Figure 2 shows the relationship between emission current and anode voltage for two different values of sandwich voltage. The emission current saturates at about 22 V and 10 V for sandwich voltages of 8 V and 6 V respectively. A calculation shows that at the higher sandwich voltage the current may be space-charge limited below saturation. From the data in the retarding field region, the mean temperature of the emitted electrons is calculated to be \( \sim 4000^\circ\text{K} \). The tube has been operating quite stably for over two months.

A characteristic effect of stimulated emission of radiation in a fluorescing material is the narrowing of the emission line as the excitation is increased. We have observed such narrowing of an emission line from a forward-biased GaAs \( p-n \) junction. As the injection current is increased, the emission line at 77\(^\circ\text{K} \) narrows by a factor of more than 20 to a width of less than \( kT/5 \). We believe that this narrowing is direct evidence for the occurrence of stimulated emission.

The GaAs junctions used in this experiment were made by diffusing Zn into GaAs doped with Te. These diodes were bonded onto a Au-plated Kovar washer and the junction was etched to an area of approximately \( 1 \times 10^{-4} \text{ cm}^2 \) as shown in the inset of Fig. 1. No attempt was made to obtain highly resonant electromagnetic modes. The diodes were immersed in liquid nitrogen and driven with current pulses as short as 50 nsec at high current levels. The light output was measured using a Perkin Elmer grating spectrometer and a Dumont 6911 photomultiplier.
At low injection levels, it was observed that more than 95% of the light was emitted in a line at 1.47 eV with a width at half maximum of 0.026 eV. From photoluminescence experiments we believe the observed line is due almost entirely to transitions between the conduction band and a Zn acceptor level. It has been theoretically shown that such transitions give rise to a relatively short radiative lifetime for holes trapped by the acceptors.

The quantum efficiency per injected electron was greater than 0.2 and perhaps close to 1 for currents greater than 10 A/cm². Similar results have been reported by other workers. However, unlike the previously reported measurements, we observe constant quantum efficiency for currents greater than 10 A/cm².

As the current was increased the half width decreased, at first only slightly, but at currents of 10⁴ to 10⁵ A/cm², the narrowing was striking, as can be seen in Fig. 1.

At high current densities heating of the p-n junction may be appreciated from a simple calculation of the ratio of the number of photons which in the steady state must be present in the crystal to the number of electromagnetic modes within both the crystal and the emission line. If one considers the relationship between the intensity of light emission from the crystal and the density of photons in the crystal, taking into account internal reflection effects, it can be shown that, at a current density of 10⁵ A/cm², a quantum efficiency of 0.5, and a line width of 0.02 eV, there are 100 photons per electromagnetic mode. With such a photon population radiative emission would be almost entirely stimulated.

Narrowing of the emission line and geometrical mode selection would yield a larger photon population per mode but in a fewer number of modes. The fact that the quantum efficiency is relatively constant for current densities at which the line width narrows rapidly (it is presumed that the photon occupation number of the reinforced modes increases rapidly) is evidence that the quantum efficiency is close to 100%.

The presence of stimulated emission probably has an effect on the high frequency characteristics of the diodes. Under conditions giving high photon occupation numbers, the response time of the diodes should be even smaller than those already reported.

The plausibility of stimulated emission in a p-n junction may be appreciated from a simple calculation of the ratio of the number of photons which in the steady state must be present in the crystal to the number of electromagnetic modes within both the crystal and the emission line. If one considers the relationship between the intensity of light emission from the crystal and the density of photons in the crystal, taking into account internal reflection effects, it can be shown that, at a current density of 10⁵ A/cm², a quantum efficiency of 0.5, and a line width of 0.02 eV, there are 100 photons per electromagnetic mode. With such a photon population radiative emission would be almost entirely stimulated.

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We are indebted to many of our colleagues at the IBM Research Center for their close cooperation.
The recent discovery of the superconducting properties of Nb-Sn compounds at magnetic-field strengths of 89,000 G (ref 1) and 150,000 G (ref 2) with current densities of the order of 10,000 A/cm² has led to a reexamination of the equilibrium diagram of the Nb-Sn system. Agafonova et al. 3 reported only one intermediate phase, Nb₅Sn, in the Nb-Sn system. Reed et al. 4 reported three intermediate phases, Nb₅Sn (beta-W structure, stable only above 775°C), Nb₂Sn (tetragonal, c/a = 1.381, peritectic, stable only between 775 and 890°C), and Nb₃Sn (tetragonal, c/a = 0.4435, peritectic at 850°C). Wyman et al. 5 reported four intermediate phases present, Nb₄Sn (m. p. 2050°C, solid solution), Nb₅Sn (peritectoid at 730°C between Nb₅Sn and Nb₂Sn), Nb₅Sn (peritectoid at 690°C between Nb₅Sn and Nb₃Sn), Nb₄Sn (peritectoid at 863°C between Nb₄Sn and liquid), and a eutectic (215°C, approximately 83 at. % Sn) between Nb₄Sn and Sn, with all intermediate phases being stable to room temperature.

This note concerns initial work by the Metallurgy of Superconducting Materials Group at the Oak Ridge National Laboratory (ORNL) which disagrees with most of the presently available information on the alloy system as to the number of intermediate phases, their melting points, and their temperature ranges of stability.

"Kunzler" 6 wires, niobium clad (0.015 in. OD x 0.007 in. ID) with a mixture of niobium and tin powder in the core, were heat treated in evacuated quartz capsules for 2, 4, and 16 hr at 1000°C and rapidly cooled, mounted, vibratory polished, 6 etched lightly, and anodized 7 at 28 V dc. The process of anodizing delineates phases by producing different interference colors on phases having different compositions, allowing distinction between phases that cannot be clearly separated in the microscope and identification of phases through a series of specimens.

Metallographic examination showed at least five phases present in all wire specimens in addition to the niobium clad and a small amount of what had been tin-etch liquid phase. Numerous particles of incompletely reacted niobium powder were present in the core in addition to a considerable amount of porosity (Fig. 1a). The amount of reaction increased with time, but the reaction was far from complete after 16 hr at temperature. X-ray diffraction measurements indicated only Nb₅Sn (ref 8) and Nb present.

Diffusion couples (1/4-in.-diam Nb tubing with a pure tin core, swaged to 0.060 in. OD) were reacted in evacuated quartz capsules for 16 hr at 800, 850, 900, 950 and 1000°C and water quenched. An additional specimen was held at 1000°C for 2 hr, cooled in 5 min to 900°C and held for 1/2 hr, cooled in 5 min to 800°C and held for 1/2 hr, and furnace cooled to room temperature.

Examination of the diffusion couples showed (Figs. 1b, c, and d) four intermediate phases present in the alloy system whose melting points were, in order of increasing tin content: phase 1, greater than 1000°C; phase 2, between 900 and 950°C; phase 3, between 850 and 900°C; and phase 4, less...