Condensation of Injected Electrons and Holes in Germanium*†

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We have demonstrated for the first time that the condensed phase of electrons and holes in germanium can be produced by carrier injection. Germanium devices at liquid-helium temperatures emit intense 708.5-meV recombination radiation characteristic of the condensed phase.

There have been extensive investigations into the collective behavior at liquid-helium temperatures of high nonequilibrium concentrations of electrons and holes in germanium and silicon.[1] The characteristic recombination lines and many related phenomena have been interpreted in terms of a first-order phase transition between an exciton gas and a metallic electron-hole liquid.[2,3] In the experiments to date the carriers have been generated by optical excitation and by a pulsed electron beam.[4] In this Letter we report experiments which demonstrate that the condensed phase can be produced by electrical injection of holes and electrons from p- and n-doped contacts.

The germanium device was 1.30 mm×1.45 mm ×1.7 mm long, $N_D - N_A = 1.0\times10^{11}$ cm^{-3}, with injecting lithium-diffused n contacts and solid-phase aluminum p contacts on opposing faces.[5] These contacts have been previously used to fabricate devices for double injection studies of high-purity germanium in the temperature range from 77 to 300°K.[6] Carriers were injected using current pulses of 10 msec duration at a repetition rate of 5.2 Hz. The recombination radiation was analyzed using a Spex 1400-II monochromator, a PbS infrared detector operated at 77°K, and a lockin amplifier. A germanium sensor was used to monitor the temperature.

The recombination radiation spectra at a current of 100 mA are shown in Fig. 1(a) for a temperature of 20°K and in Fig. 1(b) for a temperature of 2.1°K. The well-established LA- and TO-phonon-assisted exciton recombination lines at 714 and 706 meV, respectively, dominate the spectrum at 20°K. At a temperature of 2.1°K an LA-phonon–assisted line at 708.5 meV and a TO-phonon–assisted line at 700 meV characteristic of the radiation from the condensed electron-hole phase dominate the spectrum. The width of the condensed phase line is about 3.4 meV and is essentially the same as the widths reported elsewhere.[1] This value of the width has been used to estimate a carrier density of 2×10^{17} cm^{-3} for the condensed phase.

Measurement of the emission intensity as a function of distance along the sample at 2.1°K and 100 mA indicated that the condensed-phase recombination radiation came uniformly from the region between the contacts. This suggests that the condensed phase is present throughout the device. In contrast, typical optical methods have excited only the surface of the semiconductors, although experiments in which two photons are used for bulk excitation of electron-hole pairs have been reported.[7]

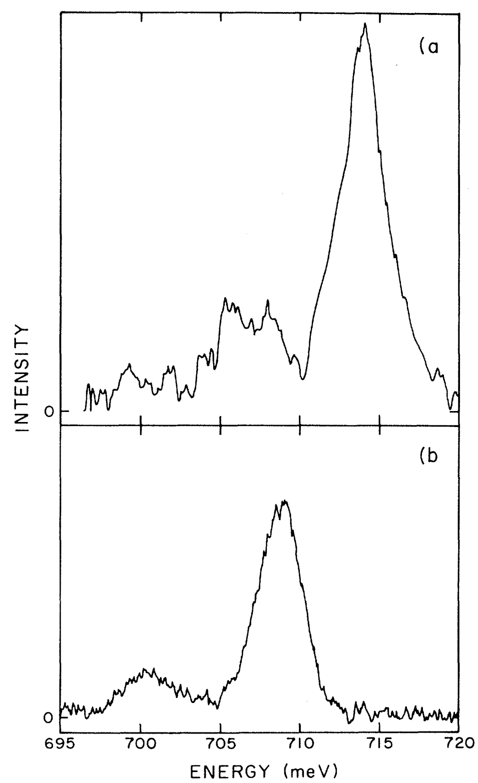

FIG. 1. Recombination-radiation spectra at a current of 100 mA and (a) $T = 20$°K; (b) $T = 2.1$°K. The vertical scale is not the same in the two parts of the figure.

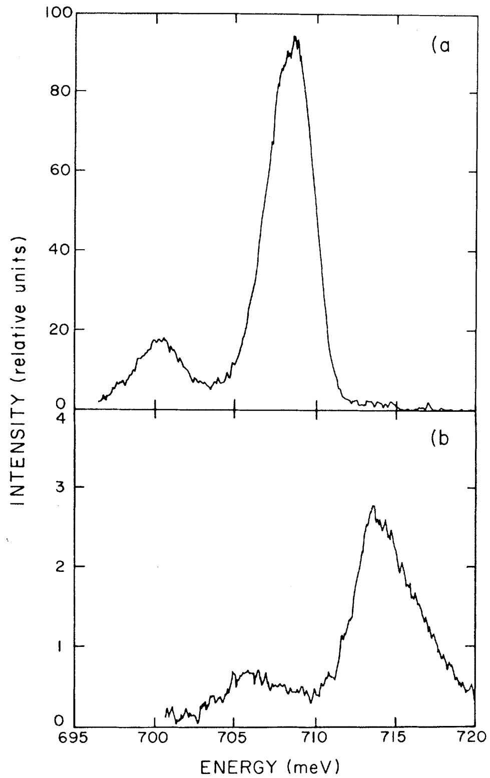

FIG. 2. Recombination-radiation spectra at 1.7°K and (a) 50 mA; (b) 600 mA. The vertical intensity scale is given in relative units. The units are the same for both parts of the figure.

We found that at low current levels (typically 1 to 100 mA) only the condensed phase recombination lines were observed and at higher currents (typically 300 to 1000 mA) only exciton lines were observed. The recombination radiation spectra at 1.7°K shown in Fig. 2 are typical of results from several devices and a variety of temperatures between 1.5 and 3.1°K. For a device current of 50 mA the spectrum [Fig. 2(a)] shows the LA- and TO-phonon–assisted condensed-phase recombination lines at 708.5 and 700 meV, respectively. At the same temperature but at a current of 600 mA, the spectrum [Fig. 2(b)] shows the LA- and TO-phonon–assisted exciton recombination lines at 714 and 706 meV, respectively. Experiments are underway to determine if the transition is due to the effects of increased electric field, increased device temperature, or possibly other causes.

In comparing Figs. 2(a) and 2(b) one can see that the intensities of the condensed-phase recombination lines are much greater than the intensities of exciton recombination lines. The high intensities of the condensed-phase lines are characteristic of previous experiments where optical excitation was used.

We feel that the injection of carriers provides a new way to study the collective properties at low temperatures of electrons and holes in germanium and possibly other semiconductors. These phenomena might also have interesting device applications. A study of the transport properties and kinetics of electrons and holes injected into germanium and silicon is in progress and will be reported shortly.

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