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CONSIDERATIONS REGARDING THE USE OF SEMICONDUCTOR HETEROJUNCTIONS FOR LASER OPERATION

by

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In a recent communication,[1] Kroemer has proposed a new injection scheme using heterojunctions for possible laser action, in which an indirect-gap semiconductor, say Ge, is sandwiched between two direct-gap semiconductors of opposite types, say n- and p-type GaAs. In our laboratory, we also have considered the feasibility of using heterojunctions for laser work based on a different scheme. Kroemer's proposal presupposes that (1) injected electrons and holes would be trapped in the center region by potential barriers at the two heterojunctions and (2) laser action would eventually occur at sufficiently high carrier injection levels. The argument presented in his article, however, is rather vague and misleading. In the present communication, we like to discuss theoretical considerations in using heterojunctions for laser operation and to present our scheme in view of these considerations.

The focal point is the life-time of excess carriers in a radiative recombination process. For degenerate direct-gap semiconductors, the life-time, given by the reciprocal of Einstein's coefficient of spontaneous emission, is of the order 10^{-11} sec. In indirect-gap semiconductors, however, the radiative recombination process must be accompanied by phonon or impurity scattering to conserve momentum and consequently, the life-time of such a process is much much longer. This is manifested by the fact that the quantum efficiency of recombination radiation in GaAs diodes is close to unity while that in Ge diodes is less than 10^{-4}. It is to be recognized that energy pumped into a diode is ultimately converted into lattice heat if not into coherent radiation. Therefore, the second assumption made by Kroemer not only needs theoretical scrunity but may become academic in practical reality.

Two principal schemes[2,3] have been proposed to achieve laser action in indirect-gap semiconductors; first, to tunnel electrons into the (000) valley

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and second, to get an admixture of the various conduction band minima and the (000) valley states through proper impurity states. The scheme to be presented here falls into the first category. Consider an n-n heterojunction of Ge - GaAs with its energy band diagram shown in Fig. 1a.

The nature of current flow across the junction has been analyzed[4] in detail by Anderson. For electrons going from Ge to GaAs or vice versa (a combination of electron emission and tunneling), both the momentum and energy of the electron are conserved. That means, if GaAs is negatively biased with respect to Ge, electrons from GaAs will go to the (000) valley of the conduction band of Ge as in direct tunneling. To prevent the (000) valley electrons from being scattered into the conduction band minima, the device must be operated at low temperatures and the doping concentration of Ge must be low. No mention is made in Kroemer's paper about scattering processes; apparently he is concerned with the indirect transition while we are interested in the direct transition in Ge. The present heterojunction scheme of getting (000) valley electrons may be superior to the tunnel scheme proposed earlier[2] because high doping concentration in the indirect-gap semiconductor is not required here.

The proposed laser structure is shown schematically in Fig. 1b, which consists of, from left to right, regions of degenerate p-type Ge, near intrinsic n-type Ge and degenerate n-type GaAs. The Ge p-n junction and the Ge-GaAs n-n junction are to supply excess holes and electrons with k(000) for radiative recombination in the center region. Degeneracy in outer regions is necessary for heavy injection to shorten the life-time of excess carrier so that the radiative recombination process may compete favorably with scattering processes. A detailed discussion may be found in Ref. 2.

It should be pointed out that even in the scheme proposed by Kroemer, excess carriers can not pile up indefinitely in the center region. After a quasi-equilibrium state is reached, the flow of electrons and holes from one outer region to the other can be described directly by quasi-Fermi levels without reference to the center region if recombination in the center region is neglected. That means, the flow of current is governed by the law of diffusion of excess minority carriers in GaAs and the situation is no better or no worse than that in a homogeneous diode. The statement made by Kroemer is misleading because it implies that great benefit can be derived from potential barriers at heterojunctions.

In summary, we believe that the function of heterojunctions in laser work is to supply the right kind of electrons with K(000) to an indirect semiconductor. In view of Anderson's work, the n-n heterojunction seems suitable for such a purpose. The question still remains, however, as to how long electrons will stay in the (000) valley. Therefore, phonon and impurity scattering should be minimized to enhance the probability of radiative recombination.

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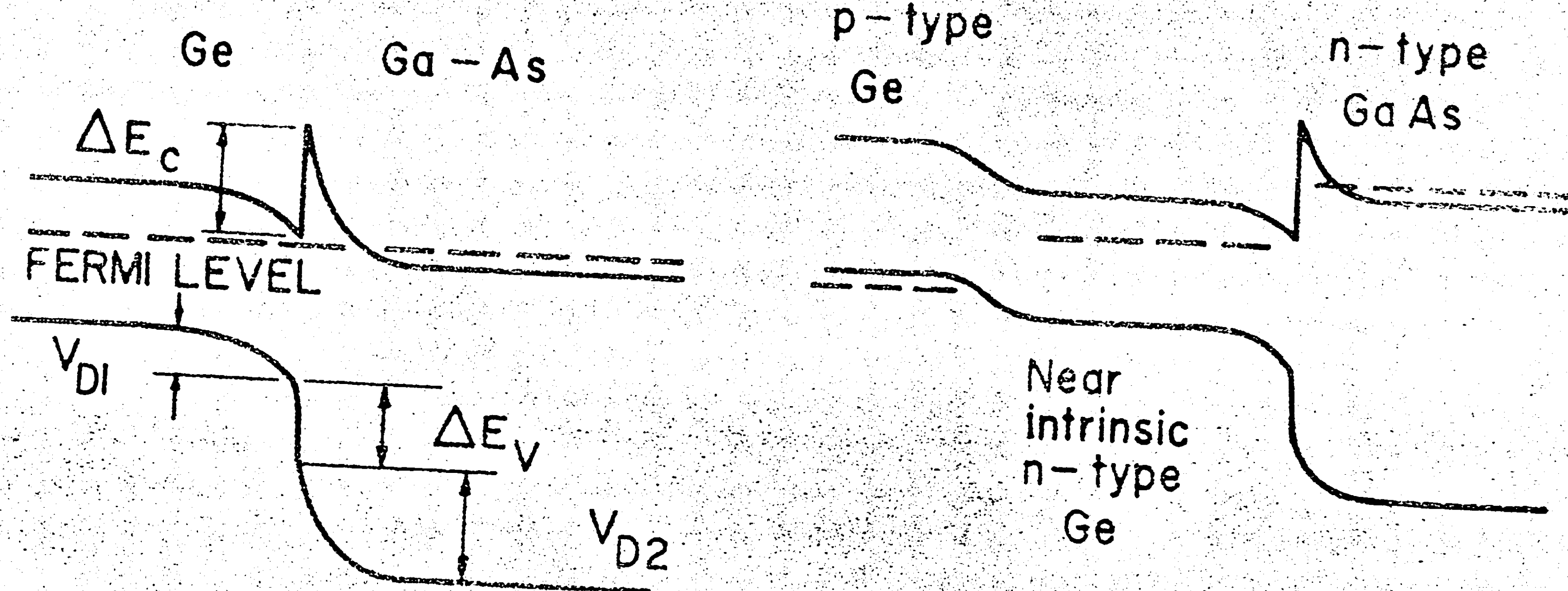

(A) (B)

Figure 1.

(A) Energy band structure of a Ge - GaAs hetero-junction where V_{D1} and V_{D2} are the built-in electrostatic potentials, and ΔE_c and ΔE_v are the differences in the conduction and valence band edges as a result of difference in electron affinity.

(B) The proposed laser structure under a forward bias condition.