Induced IR emission in silicon with heavily doped diffused quantum-well profiles

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Experiments reveal an intense IR emission induced by an external electric field in silicon containing heavily doped diffused quantum-well profiles. This emission is explained in a model of a 2D excitonic insulator.

Observing and studying the properties of excitonic insulators based on semiconductor crystals is a rather involved problem, complicated by the many ways in which charge correlations can decay in the 3D case.[1-3] In 2D and 1D semiconductor systems, one observes a sharp intensification of screening features and an increase in the binding energy of an exciton. It thus becomes possible to realize various versions of an exciton instability under conditions corresponding to a narrow-gap Mott–Hubbard insulator resulting from surface[4] and dislocation[5] dangling bonds. One consequence of the opening of a gap in the density of states of a degenerate 2D electron (or hole) gas is that it becomes possible to observe induced IR emission upon the disruption of charge/spin correlations by an external electric field. From this standpoint, silicon with diffused quantum-well profiles containing a degenerate 2D gas of holes (or electrons) is the best setting for detecting this effect by means of IR electroluminescence. In this letter we are reporting an effort to observe and study the corresponding spectra.

Boron was diffused into single-crystal silicon platelets 350 μm thick in the (100) orientation. The silicon was of n type with a resistivity of 1.0 $\Omega \cdot$ cm. In the first stage of the process, the working and back sides of the platelets were subjected to thermal oxidation. Windows corresponding to the geometry for the quantum Hall effect were then opened up on the working side of the platelets by photolithography (Fig. 1a). The p–n junctions were formed in these windows during boron diffusion from the gas phase.

The characteristics of the quantum-well diffused profiles resulting from the procedure described above, with short diffusion times, were measured by the SIMS method. The boron concentration in the diffused profile and the depth of the profile depended on the oxide thickness (d_{SiO_2}) and the diffusion temperature (Fig. 1b).

Impurity diffusion in semiconductors can be accelerated sharply when there are excess fluxes of interstitial host atoms (this is the kick-out mechanism) or vacancies (this is the dissociative vacancy mechanism), generated by the oxidized surface.[6,7] The use of thin SiO_2 layers on the surface of silicon, combined with high diffusion temperatures, leads to a sharp intensification of the kick-out mechanism for impurity diffusion (curves 1 and 2 in Fig. 1b). Thick SiO_2 layers and low diffusion tempera-

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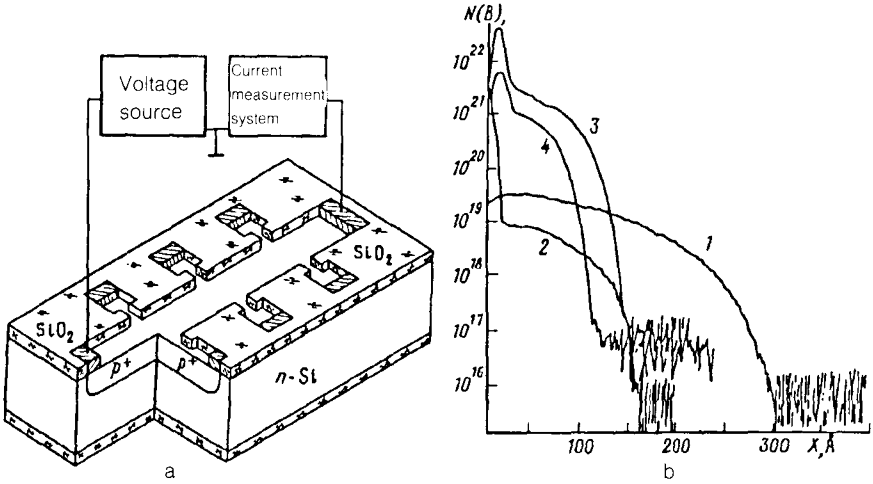

a b

FIG. 1. a: Circuit for the planar structure based on a diffused quantum-well profile of boron in silicon for current flow in the plane of the *p–n* junction. b: Diffused profiles of boron in silicon (data from SIMS measurements) obtained with a thin oxide (1, 3) and a thick one (2, 4) on the surface of the plates at diffusion temperatures of 1100 °C (1, 2) and 800 °C (3, 4).

tures, in contrast, stimulate the dissociative vacancy mechanism and sharply increase the dopant concentration (curves 3 and 4 in Fig. 1b).[7] In addition, an oppositely directed flux of interstitial host atoms or vacancies generated by the oxidized back side of the platelet can have a retarding effect on the diffusion of a dopant.[7] Accordingly, under conditions such that one or the other of these diffusion mechanisms is predominant, it is possible to produce extremely sharp diffused profiles. This capability is particularly important at short diffusion times, for which quantum-well *p–n* junctions are formed (Fig. 1b).

The passage of a direct current along the diffused quantum-well profiles (in the geometry corresponding to the quantum-Hall effect; Fig. 1a) stimulates intense IR emission. Spectra of this emission were measured (Fig. 2) with the help of an ST-50 double monochromator and a system of IR photodetectors based on cooled InSb. Figure 2 shows IR emission spectra for $T=300$ K (a,c,d) and $T=77$ K (b) for various values of the longitudinal current (*a*, *b*) in diffused quantum-well profiles of various depths (c and d). The emission intensity is seen to increase with increasing current and with decreasing depth of the diffused profile. The emissivity of the quantum-well structures is considerably lower at $T=77$ K than at room temperature. Furthermore, the emission decreases in intensity, primarily in the short-wave part of the spectrum (Fig. 2d), with decreasing boron concentration in the diffused quantum-well profile.

The sharp dip in the spectra at $\lambda=4.27$ μm corresponds to IR absorption resulting from the natural CO_2 abundance in the atmosphere. The structural features in the

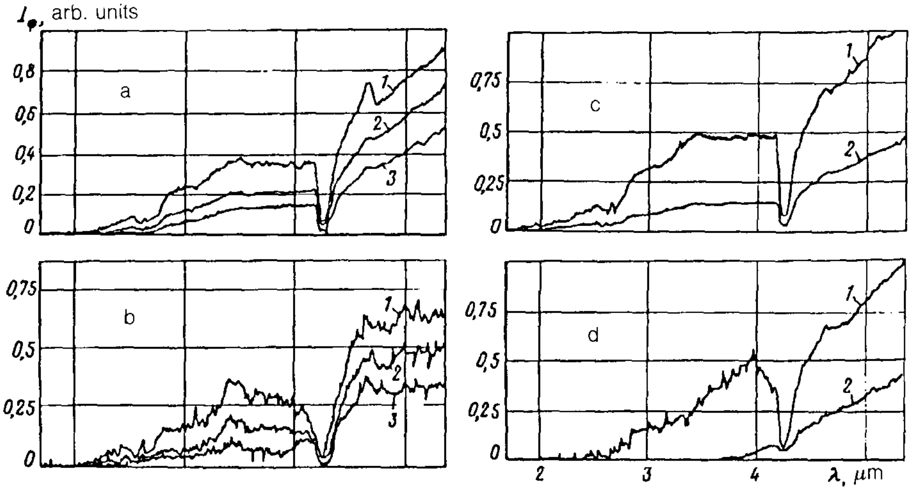

FIG. 2. Spectra of the IR emission induced by the flow of a longitudinal current in silicon $p^+ - n$ quantum-well structures at $T = 300$ K (a, c, d) and $T = 77$ K (b). For curves 2 in panels a, b, c, the profile corresponds to curve 3 in Fig. 1b; for curve 4 in panel c, it corresponds to curve 4 in Fig. 1b; for curves 1 and 2 in panel d, it corresponds to curves 2 and 1, respectively, in Fig. 1b. a: 1—The power of the emission is 900 mW/mm^2 (100 mA); 2—680 (50); 3—450 (35). b: 1—100 mW/mm^2 (250 mA); 2—80 (200); 3—45 (160). c: 1—1600 mW/mm^2 (50 mA); 2—680 (50). d: 1—360 mW/mm^2 (150 mA); 2—90 (150).

emission spectra at $\lambda = 2.66$ μm arise from residual water vapor between the source of emission and the photodetector.

As the depth of the diffused profile is increased, there is a sharp decrease in the intensity of the IR emission, accompanied by a long-wave shift of the spectrum (Fig. 2d). Diffused profiles with depths greater than 300 Å have received essentially no previous study in this wavelength region.

The results found here can be explained by the model of a 2D excitonic insulator which arises because of strong charge correlations in a degenerate hole gas in a diffused quantum-well profile (Fig. 3). Because of the intensification of screening features at ultrahigh boron concentrations (a weakening of the Coulomb interaction), a gap opens up in the density of states of the degenerate 2D electron–hole gas (Fig. 3). The binding energy of an exciton localized at a boron acceptor center in silicon corresponds to the largest gap in the density of states. It can reach 0.4 eV. This quantity is interrelated with the energy position of a deep dangling-bond level in the silicon band gap[5] (E_v+0.4 eV), since the pronounced weakening of the Coulomb interaction results in the trapping of an electron and a hole at different bonds between boron and silicon:

$$B^0 + \begin{pmatrix} e \\ h \end{pmatrix} \xrightarrow[0.044\text{eV}]{} B^- + h \xrightarrow[0.4\text{eV}]{} B^{0*}, \tag{1}$$

where B^{0*} is a negative-U center.[8]

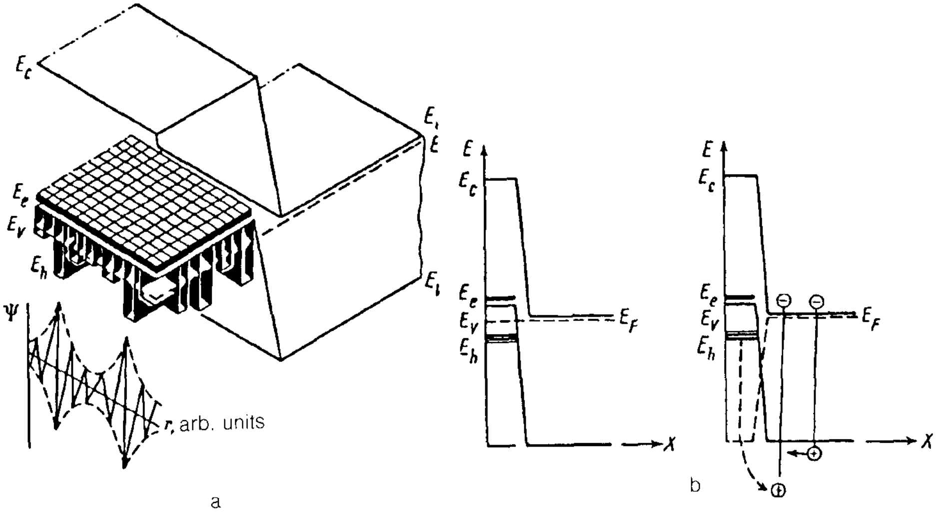

FIG. 3. One-electron band diagram of the quantum-well $p^+ - n$ junction in silicon, in 3D (a) and 2D (b, c) images. a, b) $I = 0$; c) $I \neq 0$, where I is the current along the plane of the p–n junction. Shown schematically in panel a are the disordered potential energy and the wave function of the localized charge state proposed by Anderson.[9]

A 2D exciton gas is "frozen" in an Anderson-transition regime[9] because of a disorder in the exciton localization energies at boron acceptors (Fig. 3a). As a result, the conductivity is blocked along the plane of the p–n junction, and there is a scatter in the size of the gap in the density of states against the background of the valence band (Fig. 3a). Correlations of this sort in a 2D exciton gas can be suppressed by passing a longitudinal current. Heating of the holes (Fig. 3b) can stimulate a radiative annihilation of 2D excitons. This process is apparently responsible for the IR emission observed experimentally. The characteristic plateau at $\lambda \simeq 3$ μm in the emission spectra of samples with an ultrahigh boron content (Fig. 2, a and b) agrees with the assumption that the binding energy of the 2D excitons reaches a maximum ($\simeq 0.4$ eV) with increasing degree of disorder in the localization of these excitons. At lower boron concentrations, the formation of a 2D exciton insulator in the diffused quantum-well profile is not accompanied by such a pronounced scatter in the exciton binding energies. As a result, the gap in the density of states decreases in size, and there is a corresponding long-wave shift of the IR emission spectrum (Fig. 2d). In this case, however, one does not observe a strong IR emission, because of a weakening of the Anderson-transition regime.

The fact that the IR emission is substantially weaker at $T = 77$ K than at room temperature indicates that the reconstruction of the charge correlations responsible for the formation of localized excitons is of a thermal nature [see (1) and Fig. 2, a and b]. This suggestion regarding a mechanism of thermal regeneration of a 2D excitonic insulator is also supported by the increase in the longitudinal current required for induced emission at a low temperature, which is apparently responsible for the suppression of Anderson localization (Fig. 2b).

The IR emission observed here is characterized by a high intensity in the spectral region studied at $T=300$ K. Heavily-doped, diffused, quantum-well profiles can thus serve as model entities for research on metal–insulator transitions in reduced-dimensionality systems and also for practical applications in optoelectronics.

In summary, these experiments have revealed that an intense IR emission can be induced by an electric current in heavily doped, diffused, quantum-well, boron profiles in silicon single crystals. The nature of this emission has been explained in terms of a radiative annihilation of the charge correlations responsible for the formation of a 2D excitonic insulator.

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