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Adjustment of the critical current in a Nb–$In_xGa_{1-x}As$/InP Josephson contact by light exposure

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The critical current of a Nb–InGaAs/InP Josephson junction is increased stepwise by light exposure. Shubnikov–de Haas effect measurements under illumination show that the increase of the critical current originates from photogenerated electrons in the quantum well. A further enhancement of the critical current is gained under continuous illumination. [S0003-6951(99)00229-6]

The critical current in a superconductor/semiconductor Josephson junction can be controlled by various methods. The most straightforward approach is the so-called Josephson field effect transistor, where a gate on top of the semiconductor channel is used to vary the electron concentration and thus to change the critical current.[1,2] Alternatively, the critical current can be controlled by a current of nonequilibrium carriers, which are injected via an ohmic contact into the semiconducting channel.[3] Apart from these pure electronic methods, the light sensitiveness of semiconductors can also be employed to adjust the carrier concentration of the semiconducting channel and thus to control the critical current of a superconductor/semiconductor junction.

The study of photosensitive junctions goes back to the early work of Giaever, who used CdS as a light sensitive interlayer.[4] Here, it was shown that a junction can be switched into the superconductive state after it was exposed to light. Beside CdS layers,[4,5] planar junctions with a $Pb_{1-x}Sn_xTe$ semiconductor also showed a pronounced effect on light exposure.[6]

In this letter, we will demonstrate that light exposure can be used to adjust the critical current in a superconductor/semiconductor junction with a high mobility two-dimensional electron gas (2DEG) placed between the superconducting electrodes. Two different exposure methods are employed to control the carrier concentration of the 2DEG and thus the critical current. First, light pulses are used to increase the electron concentration in the 2DEG stepwise. This method is based on the persistent photoconductance, where the photogenerated carriers remain in the semiconductor even after switching off the light source.[7] Above that, a continuous light exposure leads to a further increase of the critical current. By using this method, an increase of the critical current by 24% was obtained in our structures. Light control of a Josephson junction can be applied as a very sensitive method to adjust the critical current of Josephson junctions.

Our junctions are based on a $In_{0.53}Ga_{0.47}As/In_{0.77}Ga_{0.23}As$/InP heterostructure, which was grown by metalorganic vapor phase epitaxy. The conducting channel, where the 2DEG is located, consists of a 10-nm-thick $In_{0.77}Ga_{0.23}As$ layer. The bottom barrier of the quantum well is formed by a InP spacer layer, while the top barrier material is $In_{0.53}Ga_{0.47}As$. Details on the layer system are given elsewhere.[8] In the dark the sheet electron concentration and mobility at 0.5 K are $7.35\times10^{11}\,cm^{-2}$ and $282\,000\,cm^2/Vs$, respectively. From these values an elastic mean free path of 4.0 μm is calculated.

Electron beam lithography in conjunction with reactive ion etching (CH_4/H_2) was used to define the semiconducting channel of the junction. Subsequently, the sample was cleaned *in situ* by Ar^+ sputtering directly before the sample was covered by a 120-nm-thick Nb layer. The geometry of the Nb electrodes was defined by a second electron beam lithography step, where a Ti mask was used for an SF_6 reactive ion etching process. The width of the Nb electrodes was 6 μm. The length L of the semiconductor was 300 and 450 nm, respectively (see Fig. 3, inset). The 2DEG is contacted from the side by the Nb superconductor. The critical temperature of the Nb layers was 8.9 K corresponding to a superconducting gap of $\Delta=1.35\,meV$. The coherence length $\xi=1.5\,\mu m$ at 0.5 K is larger than L, therefore the structures can be regarded as a *short* junction. Since the elastic mean free path is larger than L, the transport takes place in the ballistic, clean limit.

The junctions were measured in a He-3 cryostat at a temperature of 0.5 K. The critical current was determined automatically by detecting the onset of a voltage drop at the junction, while the normal state resistance was measured at bias voltages larger than $2\Delta/e$. For the light exposure a red (665 nm) GaAs, light emitting diode (LED), operating at room temperature, was used. The light was guided through a plastic fiber down to the surface of the sample.

The initial critical current I_{c0} and normal state resistance R_n of the 300-nm-long junction are 3.7 μA and 65 Ω, respectively, while $I_c=4.2\,\mu A$ and $R_n=45\,\Omega$ are obtained for the 450-nm-long junction. From these values a characteristic voltage of $V_c=240\,\mu V$ is deduced for the shorter junction and 189 μV for the longer junction. The small difference in V_c shows that the intrinsic junction properties are about the same for both junctions although R_n is larger for the shorter junction. The latter effect is probably due to inhomogeneities of the Nb/2DEG interface.

The normalized critical current I_c/I_{c0} increases for both samples with increasing number of light pulses as shown in

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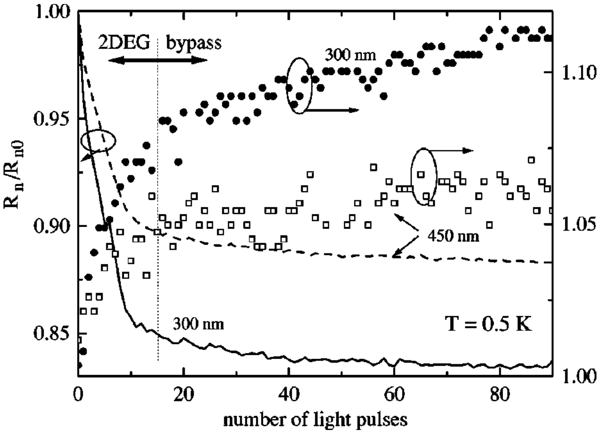

FIG. 1. Normalized critical current I_c/I_{c0} and normal state resistance R_n/R_{n0} as a function of the number of light pulses for the 300 nm as well as the 450 nm long junction at 0.5 K. I_{c0} and R_{n0} are the critical current and normal state resistance in the dark. The pulse length is 5 ms.

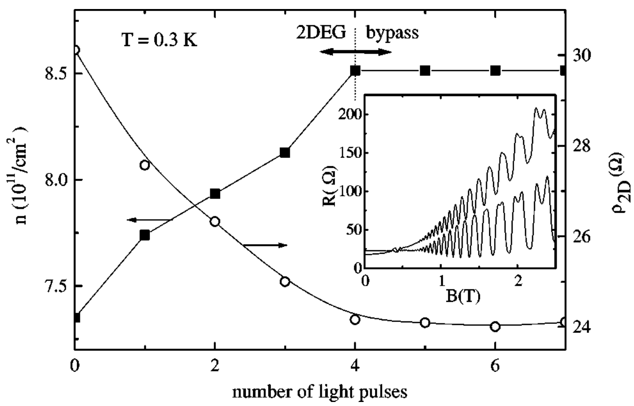

FIG. 2. Sheet electron concentration n and sheet resistance ρ_{2D} at 0.3 K as a function of the number of light pulses. The inset shows the Shubnikov–de Haas oscillation as a function of the magnetic field before illumination (lower curve) and after 7 light pulses (upper curve).

Fig. 1. The light pulses had a duration of 5 ms, with a LED bias current of 5 mA. First, the critical current increases very steeply for both samples but after more than 15 accumulated light pulses the increase of I_c/I_{c0} slows down. The final value of I_c/I_{c0} after 90 pulses differs for both junctions. For the 300-nm-long junction an increase of about 12% could be achieved, while only 6% was obtained for the 450-nm-long junction. The increase of the critical current is accompanied with a corresponding steep decrease of the normalized normal state resistance R_n/R_{n0} for up to 15 accumulated light pulses, while for a further exposure only a weak decrease is measured. If both junctions are compared, it can be seen that the 300-nm-long junction with the larger relative increase of the critical current shows at the same time a larger relative change of the resistance.

In order to relate the observed increase of I_c to the electron concentration in the 2DEG, Shubnikov–de Haas effect measurements on Hall bars were performed under illumination. The Hall bars were fabricated from the same heterostructure. Since a different sample holder was necessary for these measurements, the Hall bar was not exposed to the same intensity per light pulse. However, Shubnikov–de Haas effect measurements allowed us to determine the sheet electron concentration n and at the same time the sheet resistance ϱ_{2D} at zero magnetic field as shown in Fig. 2. First, n increases from an initial value of $7.35\times10^{11}\,\mathrm{cm}^{-2}$ after each light pulse, while after more than four pulses n keeps constant at a value of $8.45\times10^{11}\,\mathrm{cm}^{-2}$. It should be stressed, that the carrier concentration plotted in Fig. 2 only represents carriers accumulated in the 2DEG, since here the Shubnikov–de Haas oscillation frequency was analyzed. Moreover, an additional bypass channel appears if the sample is illuminated by more than four pulses. The appearance of a bypass channel is deduced from the parabolic increase of the resistance, as can be seen in Fig. 2 (inset). The photogenerated carriers are due to an excitation across the band gap of InP, as explained by Kane *et al.*[9] Electrons and holes are separated by the build-in electric field of the heterojunction. According to Kane *et al.*[9] the holes are trapped in the InP buffer layer. Up to a certain light dose, the electrons are collected in the quantum well, whereas for even higher doses the electrons are found in the InP dopant layer. The latter effect is responsible for the bypass channel. The sheet resistance ϱ_{2D} plotted in Fig. 2 first shows a steeper decrease followed by a saturation in accordance with the measurement of R_n in Fig. 1. By matching the measured drop of ϱ_{2D} to the drop of the normal state resistance R_n of the junctions it is now possible to gain information on the corresponding sheet electron concentration in the junction.

The experimental findings can be analyzed by using the model of Chrestin *et al.*[10] In this model a 2DEG in a semiconductor is considered, with δ-shaped barriers at the superconductor/semiconductor interface. The barrier strength is expressed by a dimensionless factor Z.[11] Due to the different Fermi velocities in the superconductor and the semiconductor, an effective potential step in the semiconductor has to be considered, in addition. By increasing the electron concentration in the semiconductor, this potential step is lowered.

In a preceding study, it was possible to describe the dependence of I_c on T of our junctions by the model of Chrestin *et al.*,[10] using a Z parameter of 1.0.[8] If the critical current is calculated for an increasing carrier concentration, an oscillating part due to interference effects is superimposed to the increase of the critical current with n. In our experiments, no modulation of I_c due to interferences is observed (Fig. 1). This is possibly due to the fact that this modulation is averaged out because of small length variations and fluctuations of the barrier strength. However, neglecting the oscillatory part of I_c an increase of about 21% was estimated for an increase of n from 7.35×10^{11} to $8.45\times10^{11}\,\mathrm{cm}^{-2}$ for a 300-nm-wide junction. In the experiment, I_c increases only by 8% if the concentration increases to $8.45\times10^{11}\,\mathrm{cm}^{-2}$. A possible explanation for the difference between theory and experiment is that the Nb/2DEG interface is covered by the Nb electrodes. The distance l between the Nb electrodes is smaller than the distance of the Nb/2DEG interfaces [see Fig. 3 (inset)]. Therefore, less photogenerated carriers are present in this covered area. This assumption is supported by the fact, that for the 450-nm-long junction an even smaller relative increase of I_c was observed. Here, the Nb electrode separation $l=250\,\mathrm{nm}$ was identical to the separation of the 300-nm-long junction, thus an even smaller exposure of interface region is expected due to shadowing. After more than 15 light pulses an additional conductive bypass channel ap-

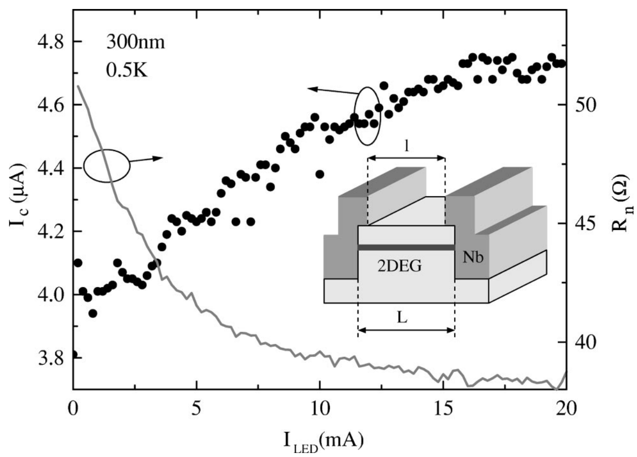

FIG. 3. Critical current I_c and normal state resistance as a function of the bias current I_{LED} of the light emitting diode (continuous illumination). A schematic of the junction geometry is shown as an inset.

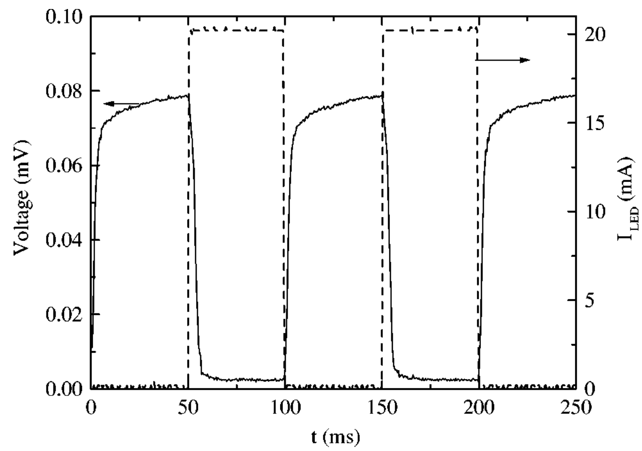

FIG. 4. Voltage drop (full line) at the junction as a function of time. The dashed line shows the bias current of the LED.

pears as deduced from the Shubnikov–de Haas effect measurements. This bypass channel is responsible for the further increase of the critical current. Since the bypass is formed by low mobility carriers in the InP material,[9] the increase of the critical current is smaller.

The critical current can be further increased by continuous illumination. As shown in Fig. 3, I_c of the 300-nm-long junction increases from an initial value in the dark of 3.8 μA up to a value of 4.7 μA if the LED bias current I_{LED} is increased to 20 mA. This corresponds to a increase of the critical current by 24%. Similar to the experiments with the pulsed light source, the normal state resistance monotonously decreases if the light intensity is increased. The initial steep increase of I_c for $I_{LED}<1$ mA can be attributed to the persistent photoconductance as discussed above. The subsequent further increase of I_c is due to the generation of electron holes pair in the top $In_{0.53}Ga_{0.47}As$ cap layer, which recombine after the light source is switched off.

The property that the critical current changes under continuous illumination, can be used to switch a junction from the normal conducting into the superconducting state by light exposure. Switching off the LED transfers the junction back in the normal conductive state, as can be seen in Fig. 4. For the demonstration of this effect, the current through the junction was fixed to a value of 0.1 μA above the maximum critical current obtained by the persistent photoconductance. The light pulses had a relative long duration of 50 ms, with $I_{LED}=5$ mA. As can be seen in Fig. 4, the switching from the normal into the superconductive state is still too slow (≈ 10 ms) for possible applications. One reason for the slow response might be that the voltage drop along the junction is small so that the carriers are only slowly removed by the electric field. Another possible explanation is that photogenerated electron and hole pairs are spatially separated by the electric field in the heterostructure so that the recombination is delayed. The latter effect might be reduced by a modified semiconductor layer system.

In summary, it was shown that the critical current in a Nb–InGaAs/InP–Nb junction can be adjusted by light pulses due to the persistent photoconductance. An increase up to 12% was observed for a 300-nm-long junction. A further increase of the critical current was gained by a continuous light exposure.

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