Carrier flow and nonequilibrium superconductivity in superconductor-based LEDs

Ryotaro Inoue1,2*, Hideaki Takayanagi3,4,2, Tatsushi Akazaki5,2, Kazunori Tanaka6,2, Hirotaka Sasakura7,2, and Ikuo Suemune7,2

1Research Center for Advanced Science and Technology, University of Tokyo, Bunkyo, Tokyo 113-8654, Japan
2CREST, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan
3Department of Applied Physics, Tokyo University of Science, Katsushika, Tokyo 125-8585, Japan
4NTT Basic Research Laboratory, Atsugi, Kanagawa 243-0198, Japan
5Central Research Laboratory, Hamamatsu Photonics K.K., Hamamatsu 434-8601, Japan
6Research Institute for Electronic Science, Hokkaido University, Sapporo 060-8628, Japan

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Transport properties of superconductor-based LEDs are quantitatively investigated. In the gate-controlled region, we confirm the realization of a new type of Josephson field effect transistor performance, in which the channel cross-sectional area of the junction can be directly modulated by the gate voltage. In the current-injected region, a superconducting critical current of the order of a few microamperes is found to be modulated by the steady current injection of the order of a few picoamperes. This ultrahigh monitoring sensitivity is considered to be due to the large energy mismatch between generated photons and superconducting pairs in the radiative recombination process, which causes the carrier flows and nonequilibrium superconductivity in the active layer. © 2014 The Japan Society of Applied Physics

Superconductor-based LEDs are expected to be a key device in quantum information technology because of their ability to generate on-demand entangled photon pairs. In spite of the large mismatch in energy scale, it is also predicted that the coherence of the superconducting pairing system can be transferred to photon systems.1–3 The radiative recombination process in superconductor-based LEDs has been investigated by using optical measurements, which revealed an enhanced oscillator strength,4 a high quantum efficiency, and a radiative recombination time rapidly decreasing with temperature.5–7 In transport measurements, in contrast, the diffusion of superconducting pairs into the active layer was demonstrated by using the DC and AC Josephson effect, and the monitoring sensitivity of the radiative recombination process was found to be several orders higher than that in optical measurements. Although the cause of this ultrahigh sensitivity has not been elucidated.5,6,8

A superconductor-based LED with one normal electrode at the p-type semiconductor side and two superconducting electrodes separated by a slit at the n-type semiconductor side can be considered as a superconductor-based three-terminal device. Superconductor-based three-terminal devices—such as the Josephson field effect transistor (JoFET),9—a supercurrent modulation device that operates via normal carrier injection (including the 0–π transition)10,11—have attracted considerable research interest from the viewpoints of not only superconducting electronics but also of the fundamental study of superconducting transport itself. Especially in the case of the superconductor-based LEDs with narrow slit width treated in this paper, most of the generated photons and photon pairs are absorbed immediately owing to the strong light confinement, and the transport properties of the device are strongly affected by the radiative recombination process. In this paper, we quantitatively analyze the transport properties of a superconductor-based LED characterized as a superconductor-based three-terminal device, and we discuss the carrier flows and nonequilibrium superconductivity that are caused by the radiative recombination process.

Figure 1(a) shows a schematic cross-sectional view of a superconductor-based LED, where a p-type indium phosphide (p-InP) layer and an n-type indium gallium arsenide (n-InGaAs) layer are stacked on a p-InP substrate, forming a p–n junction heterostructure. (For the details of device fabrication, see elsewhere.12) When positive (negative) voltage is applied to the gate electrode under the p-InP substrate, the p–n junction is biased forward (reversely). Two niobium (Nb) superconducting electrodes with a thickness of 80 nm are attached to the n-InGaAs layer, where superconducting pairs together with quasiparticles diffuse via the proximity effect. Under the forward-biased condition, normal holes injected from the p-InP layer recombine with the superconducting pairs and quasiparticles in the n-InGaAs active layer. The resultant electroluminescence (EL) emission can be detected from the slit between the two Nb electrodes, the width of which (L) is 150 nm. Figures 1(b) and 1(c) show the EL spectrum and spectrally integrated EL intensity as a function of injected current, as measured in the sample with the same composition but with a wider slit width for optical measurement.12 It is found that the EL emission of ~0.86 eV, which reflects the band structure of the p–n junction, is obtained with an intensity roughly proportional to the injected current.

The two Nb superconducting electrodes together with the n-InGaAs layer between them form a superconductor–semiconductor–superconductor Josephson junction structure. (Throughout this paper, we treat the two n-InGaAs layers shown in Fig. 1(a) as a single n-InGaAs layer.) We investigated the Josephson junction characteristics by changing the gate voltage (Vg) and/or the injected current (Iinj), at a temperature of 30 mK, using a dilution refrigerator. The measurement circuit is also shown in Fig. 1(a). In the measurement of the Josephson junction characteristics, we biased the junction in such a way that the averaged electric potential of the two Nb electrodes was kept at 0 V. Therefore, when the hole current is injected from the gate electrode, the corresponding current is extracted via both Nb electrodes. From the preliminary Hall measurement at 0.3 K, the carrier density and carrier mobility in the n-InGaAs layer were obtained as 1.4 × 10¹⁷ cm⁻² and 1.6 × 10³ cm² V⁻¹ s⁻¹, respectively, and we consider both of these values saturated in the low-temperature limit. Because the mean free path (l) and the thermal coherence length (ξ) at 30 mK are estimated to be

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with a wider slit width between the two Nb superconducting electrodes for as a function of injection. EL data are measured at 0.3 K in a similar device with a wider slit width between the two Nb superconducting electrodes for optical measurement.

\(~75\text{ nm} \text{ and } ~1.25\mu\text{m}, \text{ respectively, the Josephson junction can be considered as dirty and short } (I < L < \xi_n).\)

Figure 2(a) shows the injected hole current \(I_{\text{in}}\) as a function of applied gate voltage \(V_G\). A steady current injection of \(I_{\text{in}} = 1.6 \text{ pA} \) starts at \(V_G = 0.78 \text{ V}\). Although we obtain the typical p–n junction diode characteristic \(I_{\text{in}} \sim \exp(eV_G/\eta \kappa T)\) with a nonideal coefficient \(\eta \sim 7.7 \times 10^3\), the tendency toward saturation can be observed at \(I_{\text{in}} \gtrsim 10\text{ nA}\). The hysteretic current–voltage characteristics of the Josephson junction with \(V_G = 0 \text{ V}\) are shown in Fig. 2(b). The origin of this hysteresis has been discussed in some of the literature.\(^{13,14}\) The superconducting critical current \(I_c\) and the normal resistance \(R_n\) defined throughout a sufficiently large current range were 0.58 \(\mu\text{A}\) and 380 \(\Omega\), respectively. With temperature increasing up to 160 mK, \(I_c\) declined as \(\sim T^{-1/4}\) while \(R_n\) took a constant value. When we applied the gate voltage \((V_G)\), both \(I_c\) and \(R_n\) were found to be changed as shown in Fig. 3(a), which we will discuss in the following.

In the gate-controlled region of \(V_G < 0.78 \text{ V}\), where we do not observe steady current injection, a depletion layer remains at the boundary of the p-InP–n-InGaAs heterostructure. In this region, we succeeded in developing a quantitative explanation for the behavior of the Josephson junction characteristics \((I_c\) and \(R_n\)\) by taking into account the depletion layer thickness modulated by the gate voltage \((V_G)\). The critical current \((I_c)\) and the normal resistance \((R_n)\) can be written as follows in dirty and short junctions by using the effective mass \((m^*)\) and mobility \((\mu)\) of the carrier:\(^{14}\)

\[
I_c = \frac{e n_q h}{m^*} \frac{W[H - x(V_G)]}{L} ,
\]

\[
R_n = R_0 + \frac{1}{e n_q \mu} \frac{W[H - x(V_G)]}{L} .
\]

Here, \(L\) (150 nm), \(H\) (40 nm), and \(W\) are the length, thickness, and width of the junction, and \(n_q\) and \(n_p\) are the quasiparticle density and superconducting pair density, respectively.

For the depletion layer thickness at the boundary \([x(V_G)]\), we assumed the standard functional form of \(x(V_G) = x(0)(1 - V_G/V_G)^{1/2}\). By fitting as shown in Fig. 3(a) and using the values of the carrier density and carrier mobility estimated from the Hall measurement, we obtained \(W = 1.02 \mu\text{m}\), \(R_0 = 360.8 \Omega\), \(x(0) = 17.8 \text{ nm}\), and \(V_G = 0.7 \text{ V}\). The details of the fit process are given in the supplemental data (available at http://stacks.iop.org/APEX/7/073101/mmedia).

The effective width of junction \(W\) (1.02 \(\mu\text{m}\)) is significantly smaller than the geometrical width of junction \(W_0\) (20 \(\mu\text{m}\)), which implies that the supercurrent flows only through narrow paths in the n-InGaAs layer. Using the interfacial resistance \((R_0)\), we defined the channel resistance \((R_{\text{Ch}})\) as \(R_{\text{Ch}} \equiv R_0 - R_0\) and investigated the \(I_{\text{L}} R_{\text{Ch}}\) product, which is expected to be independent of junction dimensions and proportional to the ratio of carrier densities \([I_{\text{L}} R_{\text{Ch}} = (h/e^2 \mu) (n_p/n_q)]\) as suggested from Eq. (1). The obtained \(I_{\text{L}} R_{\text{Ch}}\) product took a constant value of 10 \(\mu\text{V}\) in the gate-controlled region, which quantitatively supports our description of the direct modulation of channel cross-sectional area by the gate voltage. This description can be regarded as a new type of JoFET, and we emphasize the difference from the conventional JoFET\(^{9}\) where the carrier density in the semiconductor (normal conductor) is modulated by the gate voltage. From the \(I_{\text{L}} R_{\text{Ch}}\) product (10 \(\mu\text{V}\)) and the quasiparticle density \(n_q\) (\(1.4 \times 10^{19}\) \text{ cm}^{-3}\)), we estimated the superconducting pair density \(n_p\) as \(3.4 \times 10^{15}\) \text{ cm}^{-3}\), the value of which is comparable to those estimated in other superconductor-based LEDs.\(^5\)
When the steady current injection takes place in the current-injected region of $V_G \geq 0.78 \text{ V}$, both $I_q$ and $R_n$ decrease. We note that the magnitude of the injected current ($I_G$) is several orders smaller than that of the modulated superconducting critical current ($I_c$). Therefore, the mechanism of this ultrahigh monitoring sensitivity is substantially different from those in conventional carrier-injected devices,\textsuperscript{10,11} reflecting the radiative recombination process. In fact, we cannot explain the behaviors of Josephson junction characteristics ($I_c$ and $R_n$) in the small current injection region of $I_G \lesssim 10 \text{ nA}$ by the increase of effective temperature of the quasiparticle–pair system in the n-InGaAs active layer because $R_n$ takes a constant value in the temperature range $\sim 160 \text{ mK}$. If we take into account the fact that the depletion layer does not exist in this region [$\chi(V_G) = 0$] and reconsider Eq. (1), the carrier densities in the n-InGaAs active layer ($n_q$ and $n_p$) are found to be the only variables that can explain the behaviors of $R_n$ and $I_c$. Using the values determined in the gate-controlled region ($R_n$ and $W$), we estimate the carrier densities in the n-InGaAs active layer ($n_q$ and $n_p$) from Eq. (1) with $\chi(V_G) = 0$, and we plot them as functions of $I_G$ in Fig. 3(b).

First, note that the sum ($n_q + 2n_p$) increases with $I_G$ throughout the current-injected region. Given the charge neutrality condition, this increase indicates that the energy of the conduction band for electrons in the n-InGaAs active layer is lowered with respect to vacuum by the current injection. This also means that the energy of the valence band for holes is raised, which is implied by the tendency toward saturation shown in Fig. 2(a). We also note that both $n_q$ and $n_p$ do not show the tendency toward saturation in the limit of $I_G \rightarrow 0$, the values of which are indicated by arrows on the left vertical axis of Fig. 3(b).

Using the flow diagram of quasiparticles and superconducting pairs schematically shown in Fig. 4, we discuss the carrier flow in a superconductor-based LED and explain the mechanism of ultrahigh monitoring sensitivity for radiative recombination. Because the total charge is conserved in the energy relaxation process following photon absorption, a current with an amount exactly equal to $I_G$ must be extracted from the n-InGaAs active layer to the Nb electrodes in the steady state. This means that the carriers flow into the conduction band of the n-InGaAs layer to compensate for the carrier loss caused by the recombination process. We define $I_q$ and $I_p$ as the current carried by quasiparticles and pairs and represent the steady-state condition as

$$I_q + I_p = I_G \equiv I_G^{(q)} + I_G^{(p)}.$$  \hfill (2)

Here $I_G^{(q)}$ and $I_G^{(p)}$ are the components of the injected hole current ($I_G$) that recombine with quasiparticles and pairs corresponding to their recombination rates.

In addition to the inflow of carriers ($I_q$ and $I_p$), the hole current injection causes a large disturbance in the quasiparticle–pair system via radiative recombination and immediate absorption of generated photons and promotes the conversion from pairs to quasiparticles. If we set the current corresponding to the conversion rate as $i$, the following condition is also required in the steady state:

$$0 = I_G^{(q)} - I_q - I_G^{(p)} - I_p + i.$$  \hfill (3)

(We define the positive direction of $i$ as the flowing direction from the quasiparticle subsystem to the pair subsystem by taking into account that the carrier charge is negative.)

In general, the conversion rate from quasiparticles to pairs ($i$) depends not only on the injected current ($I_G$) but also on the carrier densities ($n_q$ and $n_p$). However, in the small current injection region of $I_G \lesssim 10 \text{ nA}$, we can assume that the energy relaxation process of absorbed photons dominantly proceeds with the destruction of superconducting pairs and set $i \approx \alpha I_G$. Here the proportionality constant $\alpha$ is approximately equal to the ratio of the photon energy ($\hbar \omega_{\text{ph}} \sim 0.86 \text{ eV}$) to the superconducting pairing energy ($\Delta_N \sim 1.5 \text{ meV in Nb}$), i.e., $\alpha \approx \hbar \omega_{\text{ph}} / \Delta_N$. After solving Eqs. (2) and (3) with respect to $I_q$ and $I_p$, and taking into account that $\alpha \gg 1$, we obtain...
\[ I_q = -(\alpha - 1)I_G^{(q)} - \frac{G}{C_0} \approx -\alpha I_G, \]
\[ I_p = \alpha I_G^{(q)} + (\alpha + 1)I_G^{(p)} \approx \alpha I_G. \]

That is, to compensate for the conversion from pairs to quasiparticles inside the n-InGaAs active layer, the superconducting pairs flow into the n-InGaAs layer (\( I_p > 0 \)) while the quasiparticles flow out (\( I_q < 0 \)). (More accurately, the outflow of quasiparticles is a little larger than the inflow of pairs and the steady-state condition is secured by including the injected hole current.) Both \( |I_q| \) and \( |I_p| \) are larger than \( I_G \) by the factor \( \alpha \gg 1 \), which results in the high sensitivity of Josephson characteristics for monitoring the radiative recombination process.

The values of \( n_q \) and \( n_p \) in the steady state are determined as the balance points in the carrier flow. Because the superconducting pair potential is sufficiently small, reformation of pairs inside the n-InGaAs layer is negligible and the pairs lost in the energy relaxation process are compensated for only by the inflow of pairs from the Nb electrodes (\( I_p \)). In the Nb superconducting electrodes, the discrepancy of chemical potentials in the quasiparticle–pair system takes place to sustain the reformation rate necessary for the compensation, which also leads to the nonequilibrium superconductivity in the Nb electrodes. Owing to the large interfacial barriers at the Nb electrodes (\( R_0 \)), it is difficult to estimate the carrier density in the Nb electrodes (\( n_q^{(\text{Nb})} \) and \( n_p^{(\text{Nb})} \)) directly from those in the n-InGaAs active layer (\( n_q \) and \( n_p \)). However, we can say that the sudden decrease of \( n_p \) in the region of \( I_G < 10 \mu\text{A} \) reflects the decrease of \( n_p^{(\text{Nb})} \) caused by the rate-limiting reformation.

When the injected current is increased (\( I_G > 10 \mu\text{A} \)), we cannot ignore the recombination process involving quasiparticles nor the various energy relaxation processes of absorbed photons other than the destruction of superconducting pairs. Moreover, the effective temperature of the quasiparticle–pair system in the n-InGaAs active layer is increased, which causes not only damping of the compensation cycle but also suppression of \( I_q \) itself. These effects result in the gradual decrease of the current amplification factor (\( \alpha \)) and eventual breakdown of the flow model described in Fig. 4. Especially in the region of \( I_G > 0.3 \mu\text{A} \), making transport measurements of the Josephson junction characteristics under steady current injection becomes difficult whereas the spectrally integrated EL intensity reaches the sensitivity of our optical measurement system, as is shown in Fig. 1(c). The injected current (\( I_G \)), being comparable with the superconducting critical current (\( I_c \)), causes asymmetric distortion of the current–voltage curve owing to the small difference in the transparency of interfaces at the two Nb electrodes.

In conclusion, we characterized a superconductor-based LED in the strong light confinement regime as a superconductor-based three-terminal device, and we quantitatively investigated its transport properties (\( I_G \) and \( R_0 \)). In the gate-controlled region, we confirmed the realization of a new type of JoFET performance, in which the channel cross-sectional area of the junction can be directly modulated by the gate voltage. In the current-injected region, a superconducting critical current of the order of a few microamperes was found to be modulated by the steady current injection of the order of a few picoamperes. We explained this ultrahigh monitoring sensitivity for the radiative recombination process by taking into account the conversion of superconducting pairs to quasiparticles in the energy relaxation of absorbed photons and discussed the carrier flows together with the nonequilibrium superconductivity, both of which take place to compensate for the conversion.

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