Physica E: Low-dimensional Systems and Nanostructures 97 (2018) 290–295

Contents lists available at ScienceDirect

Physica E: Low-dimensional Systems and Nanostructures

journal homepage: www.elsevier.com/locate/physe

Interaction-free measurement with mesoscopic devices on a GaAs/AlGaAs heterostructure

Hiroo Azuma

Advanced Algorithm & Systems Co., Ltd., 7F Ebisu-IS Building, 1-13-6 Ebisu, Shibuya-ku, Tokyo 150-0013, Japan

A R T I C L E I N F O

Keywords:
Electron quantum optics
Interaction-free measurement
Quantum point contact
Shot noise
Tunnelling microscope
Two-dimensional electron gas

A B S T R A C T

In this paper, we propose a method for implementing the interaction-free measurement (IFM) with mesoscopic devices fabricated on a high mobility GaAs/AlGaAs heterostructure, where a two-dimensional electron gas (2DEG) system is buried, at low temperature. The IFM is amazing evidence of nonlocality of the quantum mechanics because the IFM offers us the capability to detect the existence of an object without interaction with it. A scheme of Kwiat et al. for realizing the IFM lets a probability that we fail to recognize the presence of the object be as small as we like, using the quantum Zeno effect. Constructing an interferometer of Kwiat et al. for the IFM, we make use of techniques of electron quantum optics and tunnelling microscopes for the 2DEG. We examine a shot noise of an electric current flowing through the interferometer. Our method for performing the IFM aims at achieving a milestone of quantum information processing in mesoscopic systems.

1. Introduction

In this paper, we propose a method for implementing the interaction-free measurement (IFM) with mesoscopic devices. In 1981, Dicke proposed an early concept of the IFM [1]. Elitzur and Vaidman starts modern discussion about the IFM by taking up the following problem [2,3]: “Suppose there is an object such that any interaction with it leads to an explosion. Can we locate the object without exploding it?”

For example, we assume the object that absorbs an interrogating photon with strong interaction if the photon comes near the object in distance. We want to examine whether or not the object exists in a black box without its absorption of the interrogating photon. Elitzur and Vaidman show that the Mach-Zehnder interferometer works as implementation of the IFM. However, their scheme is very simple and a probability of detecting the object without its absorption for one interrogation is equal to 1/4. If repetition of interrogations is allowed, the probability becomes 1/3. Moreover, if the reflectivity of the beam splitter is adjusted, it is improved and reaches almost 1/2.

Kwiat et al. find a more refined experimental method for realizing the IFM [4]. They put the absorbing object in an interferometer which consists of many beam splitters, and inject a photon into it to examine whether or not the object exists. In the scheme of Kwiat et al., the quantum Zeno effect plays an important role and its efficiency, namely its detection rate for the absorbing object, approaches unity asymptotically as the number of the beam splitters grows. In Ref. [5], this scheme is actually performed with high efficiencies of up to 73% in experiments.

Moreover, Paul and Pavičić propose another experimental setup for the IFM. Making use of the Fabry-Pérot interferometer, they let their own scheme be very practical [6]. Paul and Pavičić's scheme is experimentally demonstrated by two research groups operating in Sweden and Japan with efficiencies around 80% and 88%, respectively [7,8].

As mentioned above, many researchers in the field of quantum information science are interested in an experimental demonstration of the IFM. This is because the IFM is not only a strange aspect of the quantum mechanics but also an important element in quantum information processing. If we obtain skill in executing the perfect IFM, we can perform various operations of quantum information processing. For example, Pavičić points out that techniques for the IFM improve the atom-photon controlled-NOT gate [9]. Azuma discusses how to take the Bell-basis measurement and how to construct the controlled-NOT gate by using the IFM [10,11]. In Ref. [12], Azuma examines the IFM with an imperfect absorber.

So far, in almost all setups of the IFM, quantum interrogation of the absorbing object has been performed with a photon. Most researchers prefer the photon for the quantum interrogation because it is suitable to construct the interferometer and pieces of equipment needed for building the interferometer, such as beam splitters, mirrors, and so on, are generally available.

However, some attempts to utilize an electron as the interrogating particle for the IFM are undertaken. In Ref. [13], the Aharonov-Bohm

E-mail address: hiroo.azuma@m3.dion.ne.jp.

https://doi.org/10.1016/j.physe.2017.11.016
Received 19 August 2017; Received in revised form 11 November 2017; Accepted 17 November 2017
Available online 21 November 2017
1386-9477/

ring with asymmetric electron injection is employed for detection of electron dephasing, and this phenomenon is interpreted as the IFM. In Ref. [14], the IFM based on the integer quantum Hall effect is proposed.

If we obtain the ability to accomplish the IFM with the interrogating electron, we can apply the quantum information processing to quantum bits implemented with electrons in a fluent manner. We can construct quantum information processors from semiconductor devices. This is the primary motivation of the current paper.

In this paper, we think about a two-dimensional electron gas (2DEG) system, which appears in a high mobility GaAs/AlGaAs heterojunction at low temperature [15,16]. If we perform experiments at near absolute zero temperature, $T \simeq 0$ K, the mobility of the confined electrons being free to move in two dimensions is on the order of $\mu = e\tau/m^* \simeq 1.0 \times 10^2 \mathrm{m}^2\mathrm{V}^{-1}\ \mathrm{s}^{-1}$. Because the effective mass of the electron in GaAs is given by $m^* = 0.067 m_{\mathrm{e}}$, its averaged relaxation time is estimated at $\tau \simeq 3.81 \times 10^{-11}$ s around.

Moreover, the Fermi energy of GaAs is given by $E_{\mathrm{F}} = 0.014$ eV and we obtain the Fermi velocity $v_{\mathrm{F}} = \sqrt{2E_{\mathrm{F}}/m^*} \simeq 2.71 \times 10^5\ \mathrm{ms}^{-1}$, so that the elastic mean free path of the electron in GaAs is approximately equal to $l = v_{\mathrm{F}}\tau \simeq 1.03 \times 10^{-5}$ m. Thus, if we fabricate a nanostructure system whose typical length is smaller than the elastic mean free path l on the GaAs/AlGaAs heterojunction, particles move in the active region without scattering. This ballistic transport is one of the astonishing characteristics of the mesoscopic system.

To perform the scheme of Kwiat et al. for the IFM in the 2DEG system, we make use of techniques of electron quantum optics for implementation of the single-electron source and the beam splitter [17–20] and the tunnelling microscope for realizing the absorbing object [21]. The electron quantum optics is a particular perspective on electronic ballistic transport in quantum conductors and it aims a counterpart of orthodox photon quantum optics. These topics belong to the mesoscopic physics, which treats quantum transport of electrons and holes confined in one or two dimensions.

In the interferometer of Kwiat et al., we let electrons travel along a quantum wire one by one with a constant time interval. Moreover, we replace the absorbing object with a probe of the tunnelling microscope. Thus, varying a voltage applied to the tip of the microscope, we can adjust a probability that the probe captures the electron with ease. We examine a shot noise of the electric current flowing through the interferometer [22–27].

Detection of the 2DEG with the tunnelling microscope is experimentally realized in Ref. [28]. Direct observation of the Landau quantization with the tunnelling spectroscopy is reported in Refs. [29,30]. Hence, we can expect the tunnelling microscope to detect the 2DEG through a thin layer of AlGaAs on the heterojunction.

This paper is organized as follows. In Section 2, we give a brief review of the IFM. In Section 3, we explain how to implement the IFM with the 2DEG system. In Section 4, we study the shot noise of the electric current in the interferometer of Kwiat et al. with an imperfect absorber. In Section 5, changing the absorption coefficient of the object by adjusting the voltage applied to the tip of the tunnelling microscope, we evaluate the success probability of the IFM. In Section 6, we give a brief discussion.

2. A brief review of the IFM

In this section, we explain the scheme of the IFM proposed by Kwiat et al. This section is a short review of Refs. [2–4]. The facts described in this section are utilized in Refs. [10–12].

We start by considering an interferometer that consists of N beam splitters as shown in Fig. 1. The beam splitters divide the interferometer into two parts, the upper and lower halves. We write the upper and lower paths as a and b in the interferometer, respectively. We can regard Fig. 1 as a series of joined Mach-Zehnder interferometers. We describe a state where one photon travels on the paths a as $|1\rangle_a$ and a state where no photon travels on the paths a as $|0\rangle_a$. A similar notation is applied

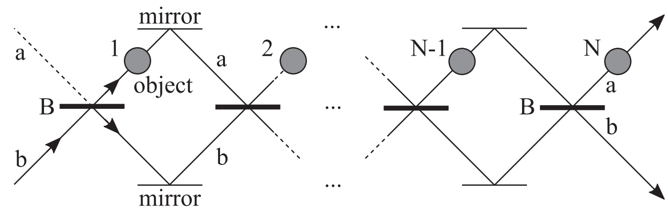

Fig. 1. The interferometer of Kwiat et al. for the IFM.

to the paths b, as well. The beam splitter B in Fig. 1 works as follows:

$$B: \begin{cases} |1\rangle_a|0\rangle_b \to \cos\theta|1\rangle_a|0\rangle_b - \sin\theta|0\rangle_a|1\rangle_b, \\ |0\rangle_a|1\rangle_b \to \sin\theta|1\rangle_a|0\rangle_b + \cos\theta|0\rangle_a|1\rangle_b. \end{cases} \quad (1)$$

The transmissivity and reflectivity of the beam splitter B are given by $\mathcal{T} = \sin^2\theta$ and $\mathcal{R} = \cos^2\theta$, respectively.

Let us put a photon into the lower left port of b in Fig. 1. If an object does not exist on the paths, the state of the photon coming from the kth beam splitter is given by

$$\sin k\theta|1\rangle_a|0\rangle_b + \cos k\theta|0\rangle_a|1\rangle_b \qquad \text{for } k = 0, 1, \ldots, N. \quad (2)$$

If we set $\theta = \pi/(2N)$, the photon coming from the Nth beam splitter flies away to the upper right port of a with probability unity.

Next, we consider the case where a photon-absorbing object exists on the paths a. We assume that the object is put on every path a that comes from each beam splitter and all of these N objects are the same one. The photon put into the lower left port of b cannot fly away to the upper right port of a because the object absorbs it. If the incident photon flies away to the lower right port of b in Fig. 1, it has not traveled through the paths a in the interferometer. Thus, a probability that the photon flies away to the lower right port of b is equal to a product of the reflectivities of the beam splitters, and it is given by $P = \cos^{2N}\theta$. In the limit of $N \to \infty$, P approaches unity asymptotically as follows:

$$\begin{aligned} \lim_{N\to\infty} P &= \lim_{N\to\infty} \cos^{2N}\left(\frac{\pi}{2N}\right) \\ &= \lim_{N\to\infty} \left[1 - \frac{\pi^2}{4N} + O\left(\frac{1}{N^2}\right)\right] \\ &= 1. \end{aligned} \quad (3)$$

From the above considerations, in the large N limit, we conclude as follows: (1) If there is no absorbing object in the interferometer, the photon flies away to the upper right port of a. (2) If there is the absorbing object in the interferometer, the photon flies away to the lower right port of b. Hence, we can examine whether or not the absorbing object exists in the interferometer.

3. Implementation of the IFM with the 2DEG

To implement the IFM with the 2DEG buried in the GaAs/AlGaAs heterojunction, we have to prepare the following three elements: a single-electron source, a beam splitter, and an absorbing object. In this section, we consider how to construct these three elements in the mesoscopic system.

Before going into details of the mesoscopic devices, we study the 2DEG that offers a system of high mobility electrons [15,16]. As shown in Fig. 2, the heterojunction generated with layers of Si-doped n-type AlGaAs and GaAs causes a quantum well, into which mobile electrons supplied by n-type AlGaAs drop. Thus, a thin depleted AlGaAs layer arises. Because the quantum well forms a steep valley with narrow width $\Delta z \simeq 8.5 \times 10^{-9}$ m and it is shorter than the Fermi wavelength of the mobile electrons, they are confined in the xy plane. Moreover, the valley is located in the GaAs layer where no dopant impurities exist, so