1. INTRODUCTION

In steady state, the Schroedinger equation which governs the motions of electrons in microscopic scale has the same equation form except for constants to the Helmholtz equation for electromagnetic wave. This fact induced a concept of electron wave device, where wavefront phenomenon for hot electron were applied to its operation principle[1]. It is well known that useful and fundamental mathematical operations such as Fourier transform can be executed as a parallel computation by modulating wavefront of electromagnetic wave. Thus, it would create novel functional devices when we realize and control wavefront conversions of hot electron causing such parallel computations in solid.

However, there is an essential difference between electron wave and electromagnetic wave due to quantum statistical nature of electrons and photons. Photon is one of the Bose particle and likely to condense to single quantum state. Thus electromagnetic wave can propagate maintaining spatial coherence with arbitrary high energy density. However, electron obeys the Fermi statistics and single quantum state can be occupied by one electron, that is, including spin degeneracy, only two electrons can posses single wavevector. Thus it is exclusive to earn spatial coherence and current level in electron wave. Therefore, to understand ability of the electron wave device, it is crucial to explore “coherent emitter” from which hot-electron wave with ultimate compatibility for both wavefront spread and current level.

We have proposed an idea of emitter, where a Fermi level of a doped source relative to an energy level of double-barrier resonant tunneling structure next to the source is adjusted by the source and back gate voltage to produce coherent and high current electron wave [2]. However, it was pointed out there, a random distributions of individual doping ions induces fluctuations of the resonant level and precisely controlled wavefront spread cannot be obtained. We must resolve the problem.

In this paper, in order to reply the problem, we give a new structure for the coherent emitter where a product of the wavefront spread and current density of emitted hot-electron still becomes ultimately maximum and performances and design of the emitter are presented.

2. COHERENT EMITTER WITH TWO-DIMENSIONAL ELECTRON GAS SOURCE
In Fig. 1(a), we propose a new structure for coherent emitter where hot electron is emitted via a quantum well source made of an *intrinsic* GaInAs and therefore free from random dopants distribution. Electrons are supplied from contact region adjacent to the quantum well where electron forms two-dimensional electron gas (2DEG) and an amount of coherent hot-electron current corresponding to an energy difference between the Fermi level in the contact region and the quantized level in the quantum well is emitted to a device active region where wavefront modulation to those emitted hot electrons is realized. As was mentioned in ref. 2, we also need a control electrode called gate to terminate all of the electrostatic force line from electrons in the quantum well and potential distribution in the active region is kept during control of emission currents. We employ a Schottky collector to avoid a current flow from the collector to the active region when there exists an attractive potential in the active region as in the case of a solid-state biprism[3].

An adjustment procedure to emission current is as follows. First, we apply a voltage difference between $V_G$ and $V_C$ to achieve flat band condition for whole of the device while $V_G=V_S$ is kept. Then, as is indicated in Fig. 1(b)(2), $V_G$ is slightly moved to negative from the flat band voltage to make an electric field in the active region directed so as to sweep energy relaxed electrons into the collector electrode and avoid any charge build up in the active region. These procedures to get flat band potential must be made without precise knowledge of the Fermi energy of the gate and the Schottky barrier in the collector. However, it would be accomplished by adopting capacitance-voltage characteristics as will be mentioned later.

The last step is to adjust the source voltage $V_S$ so that an appropriate energy difference between the source Fermi level and the quantized level is achieved, as shown in Fig. 1(b)(3). Also in this case, we do not know exact value of the quantized level but from an experimental data of the emission current vs. the source voltage $V_S$ we would deduce a relation between the energy difference vs. $V_S$.

In the following sections, we confirm our scenario mentioned above and analyze...
performances of the proposed coherent emitter.

3. COHERENT CURRENT: PRODUCT OF CURRENT DENSITY AND WAVEFRONT SPREAD

We give a relation between the wavefront spread and emission current. The 2DEG is formed by a thick InP gate barrier which prevents any electron flows between the source and the gate, and a rather thinner InP barrier which permit current flows from the source to the active region (see Fig. 1). Because of this coupling between the source and the active region, the quantized level becomes broaden and electrons in the source have finite life time \( \tau \) to stay at the source. The emission current density at 0 K can be written as

\[
J = \int_{E_0}^{\mu_S} \frac{q}{\tau} \frac{m}{\pi \hbar^2} dE = \frac{q}{\pi \hbar^2} \left( \mu_S - E_0 \right),
\]

where \( q \) is elementary charge, \( \hbar \) is the Dirac’s constant, \( \mu_S \) and \( E_0 \) are a Fermi level and a quantized level in the source respectively, and \( m \) is a effective mass in the source. From ref. 2, a diameter of wavefront spread is

\[
D = \frac{\pi \hbar}{\sqrt{2m(\mu_S - E_0)}}. \tag{1}
\]

An energy broadening \( \Delta E \) is related to the lifetime by a relation \( \Delta E = h/\tau \) where \( h \) is the Planck constant. Then, quantity indicating attainable coherent current for any planar emitter, that is, a product of current density and wavefront spread for our emitter is

\[
J \pi \left( \frac{D}{2} \right)^2 = \frac{q \pi}{16} \Delta E.
\]

The above value is the ultimate one[2].

![Figure 2: Normalized energy spectrum in the quantum well (a) and, diameter of electron wavefront spread and emission current (b).](image)

4. WAVEFRONT SPREAD AND EMISSION CURRENT

Next, we address quantitative values of wavefront spread and emission current At finite temperature, thermal energy broadening of the Fermi energy in the source significantly affects attainable wavefront spread and we modify eq. (1) to

\[
D = \frac{\pi \hbar}{\sqrt{2m\left[ (\mu_S - E_0)^2 + (k_B T)^2 \right]^{1/2}}}. \tag{2}
\]

Also, the emission current is

\[
I = A \frac{q}{\tau} \int_{E_0}^{\infty} \frac{m}{\pi \hbar^2} dE \left( \frac{e^{(E-E_0)/k_B T}}{e^{(E-E_0)/k_B T}} + 1 \right),
\]

where \( A \) is an area of the quantum well source.
On estimations of emission current, we need to calculate a lifetime $\tau$. A energy spectrum in the quantum well is shown in Fig. 2 (a) when a well width of 15 nm and barrier thickness of 5 nm are assumed. From the figure, $E_0=24.7170$ meV and $\Delta E=0.1878$ meV from the bottom of conduction band, and this leads $\tau=22.0$ ps. Using this value of life time and assuming $A=200[nm]\times500[nm]$, the emission current and wavefront spread at 4K are calculated against $\mu_S$ as shown in Fig. 2 (b). When $\mu_S-E_0=1$meV, a wavefront spread $D=94$nm and an emission current $I=124$nA are obtained. These values are sufficient for a detection of hot-electron wavefront phenomena in a device fabricated by state-of-the-art technology.

5. MAINTAINING QUANTUM WELL BEING EQUILIBRIUM WITH CONTACT REGIONS

In order for our emitter to work, the quantum well region must be in equilibrium with adjacent contact regions, that is, the Fermi level in the quantum well must be well defined and have the value $\mu_S$. However, the supply current from the contact to the quantum well is carried by electrons with kinetic energy $\mu_S-E_0$, which is so small and about 1 meV as mentioned in the last section, and thus it is not clear whether this supply current can overcome the emission current to keep the quantum well being equilibrium with the contact regions. The criterion is

$$L \frac{1}{2} < v_t \tau.$$

where $L$ is a lateral length of the quantum well region between two source contact regions. $v_t$ is the transverse velocity of electron normal to the emission current. When we use averaged one for $v_t$ with $\mu_S-E_0=1$meV and 22.0ps for $\tau$ derived in the last section, then $L<2.92\mu m$ is obtained. This can be easily realized.

6. DETECTING FLAT BAND CONDITION

As the final discussion, we address to a question posed in section 2, that is, “How can we detect flat band condition?”. In a real device, we do not know precise values of any doping densities and the Schottky barrier height and this fact naturally induces the above question. Monitoring capacitance-voltage characteristics during sweeping the gate voltage $V_G$ can do it. The source voltage $V_S$ is kept to be equal to $V_G$ during the sweep. The measured capacitance is a differential capacitance and given by

![Figure 3: Calculated capacitance-voltage characteristics.](image)
\[
C_G = \frac{dQ}{d\phi_G} = \frac{-q\varepsilon |N_d - n(\phi_G)|}{\sqrt{-2q\varepsilon \int_\phi^h [N_d - n(\phi)]d\phi}},
\]
where \(\phi_G\) is a voltage drop in the gate region. \(N_d\) is a donor doping density and \(n\) is electron density derived by the Fermi-Dirac integral of order \(1/2\). In the derivation, we ignored source electrons since they induce negligible band bending. Calculated \(1/C^2\cdot\phi_G\) characteristics are depicted in Fig. 3 when a temperature of \(4K\), \(d_i=200nm\), and the gate Fermi energy \(\mu_G\) is assumed to \(5, 15, 30\)meV. From the figure, we recognize that when we assume lower gate doping density, that is, \(\mu_G=5\)meV, then flat band condition can clearly detected.

7. SUMMARY
In summary, we have proposed a new coherent emitter which is free from random distribution of doping ions. Performances and designs have been presented for the emitter. Up to now, it may be difficult to fabricate, however, the coherent emitter has sufficient abilities to observe hot-electron wave phenomena in solid.

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REFERENCES