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Invited

Monolithic Superconductor-Base Hot-Electron Transistor with High Current Gain

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A GaAs/Nb(or NbN)/InSb monolithic superconductor-base hot-electron transistor was newly developed and its transistor action was investigated theoretically and experimentally. The common-base current amplification factor as high as 0.8 was attained for a 200Å -thick Nb base when the device was cooled down to the cryogenic temperatures. The epitaxial growth of NbN (base) on the passivated semiconductor surface (emitter) is also demonstrated.

§1. Introduction

With recent striking progress of the thin film fabrication technologies, a hot-electron transistor (HET) has again been attracting much interest. The HET's are capable of ultra-high speed signal processing as well as sufficient current amplification owing to a possible quasi-ballistic electron transport in their thin base layers. In the latest high-speed device trend, Beneking put the monolithic HET at the corner point of the minimum product of the dissipation power and the switching delay.[1]

Until now, hot-electron transfers have mainly been demonstrated on all semiconductor junction structures. Namely, the planar-doped-barrier-transistor (PDBT), the heterostructure bipolar transistor (HBT), the hot-electron transistor (HET) and the tunneling hot-electron transfer amplifier (THETA) are the successful devices ever reported, in which the quasi-ballistic electron transports have been observed.[2-5] The success of growing high-quality metal-silicide on Si single crystal and/or the Si epitaxial over-growth onto the metal-silicide/Si hetero-structure have made it feasible to attain the transistor action of the semiconductor-metal-semiconductor junction devices. In this metal-base transistor, the electron travelling speed is predicted to be much higher than in the semiconductor base. Hensel, Levi, Tung and Gibson have obtained a high current gain (common-base) α of 0.6, and Rosencher, Delage, Arnaud D'Avitaya, D'Anterroche, Belhaddad and Pfister of 0.2 both from experiments on epitaxially grown $Si/CoSi_2/Si$ system.[6,7] After this, the GaAs/W/GaAs system was introduced to the transistor device by Derkits et al, the device being working rather like a permeable base transistor.[8] Concerning their practical use, however, they still have many problems. The most serious one may be the presence of a base resistance. In order to establish a high transport efficiency of hot carriers, the base layer has to be made as thin as possible. A thin base layer, however, unavoidably results in a high base circuit resistance which, in turn, limits the cut-off frequency in the range out of our expectation.

A superconductor-base hot-electron transistor, hereafter referred to as a Super-HET, is a very promising candidate which can almost completely solve this problem.[9] This is due to the shunting effect of the base resistance (quasi-particle resistance) by the small super-conducting kinetic inductance (pair-particle inductance). In consequence, the dramatic improvement of the high-frequency characteristics can be expected to obtain with the Super-HET. The other problems inherent in the conventional metal-base transistor, e.g., the quantum mechanical reflection, back-scattering at the collector barrier and so on, are also expected to be solvable by choosing appropriate material combinations. Among many semiconductor materials, InSb seemed to be the most desirable material for the collector barrier of the Super-HET due not only to its low barrier height, but also to the electron wave-function matching between the superconductor base and the collector, leading to the null reflection of electron flow at the interface.[10]

In the present work, the design and the preliminary experiments on the Super-HET have been carried out. This new transistor comprising GaAs/Nb(or NbN)/ InSb heterostructures provided a significantly improved amplification factor as high as 0.8 in accordance with our theoretical expectation.[11]

§2. Design of the Super-HET

The major causes of the current loss during electron transport from the emitter to the collector in HET's are the quantum mechanical reflection at the base-collector junction and both the elastic[12] and inelastic electron collisions inside the base layer.

As to the former one, the quantum mechanical transmission (QMT) coefficients α_B for Nb-InSb, Nb-GaAs and Nb-Si are calculated using the MacColl model[13] as a function of the excess energy of the incident electron with respect to the collector barrier peak. A glance of Fig. 2 tells that, for InSb collector, the excess energy of 0.2eV is sufficient to obtain $\alpha_B \doteqdot 1$. This is a result of the electron velocity matching in Nb base and InSb collector layers.

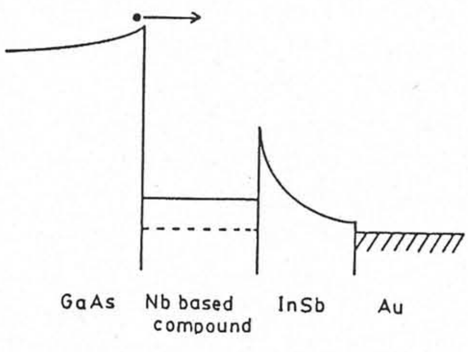

Fig.1 Energy band diagram of the Super-HET.

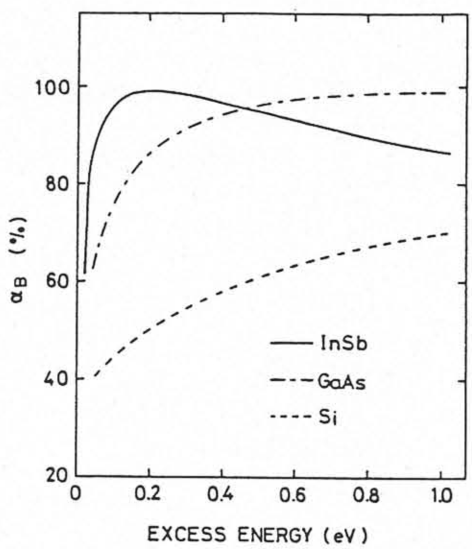

Fig.2 Quantum mechanical transmission.

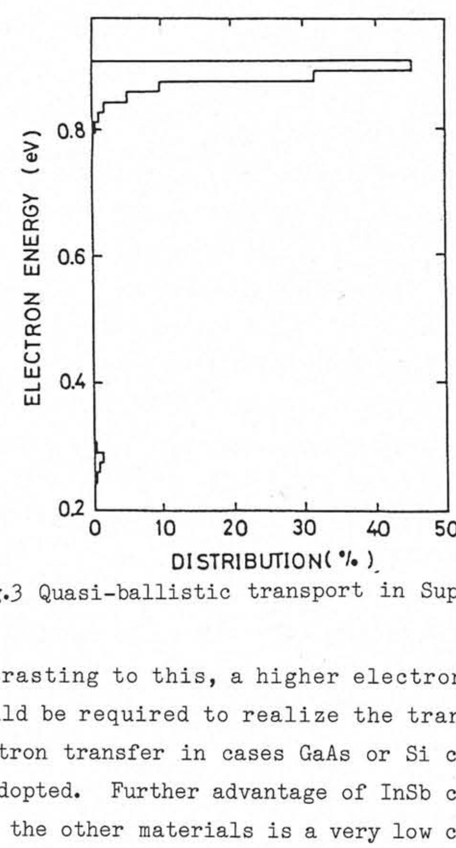

Fig.3 Quasi-ballistic transport in Super-HET.

Contrasting to this, a higher electron energy should be required to realize the transparent electron transfer in cases GaAs or Si collector is adopted. Further advantage of InSb collector over the other materials is a very low collector barrier height. This facilitates the emitter material selection.

By taking the electron-acoustic phonon scattering and the electron-electron scattering into account, we have the energy spectrum of the arrival electrons at the collector junction. An example of the Monte-Carlo simulation carried out for 5000 samples injected from GaAs emitter into 100 Å thick Nb base is given in Fig. 3, showing that more than 90% of electrons come into the collector InSb.

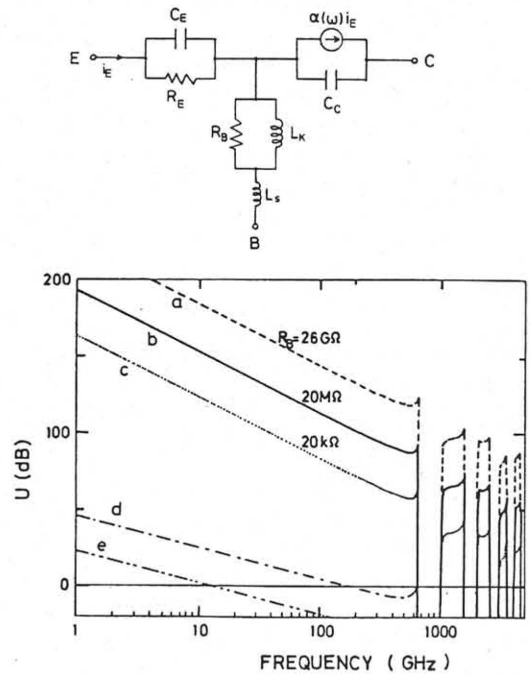

Fig.4 Unilateral power gain. Curves (a)-(c) are of the Super-HET, (d) of the Au-base, and (c) of GaAs-base. The base is 100Å thick.

The Super-HET is characterized by the shunting of the base circuit resistance R_B by the kinetic inductance L_K, as shown in Fig. 4(a), where R_B denotes the quasi-particle resistance, and varies with the temperature and the superconductor materials. The unilateral power gain calculated for 2μmx2μm wide junctions are drawn in Fig. 4(b). As compared to HET's with Au or GaAs base, the Super-HET reveals the ultra-high frequency power gains. By thinning the InSb collector barrier, the maximum frequency of the oscillation reaches 1600GHz.

§3. Experiments

3-1. Preliminary experiment on Super-HET.

The requirements imposed on the emitter material are twofold: (i) a long ballistic mean-free-path of hot-electrons which gives rise to a high injection efficiency and (ii) a superior Schottky barrier formed at the interface of the emitter and the refractory superconductor base. Among many materials, GaAs was chosen as a most preferable material. As shown in Fig. 5, the emitter junction area (80μm in dia.) was defined by anodic oxidation of GaAs itself, on which Nb or NbN (200-600Å) were sputter-deposited by rf sputtering (or reactive sputtering). The collector InSb barrier was also formed by sputtering using the non-doped InSb target.

The typical I-V curves of the Super-HET measured at 4.2K are drawn in Fig. 6, showing the common-base transistor characteristics. At least at present, the data scatter is pretty large and some samples never showed the transistor action. Among them, the top values of the common-base current gain are plotted in Fig. 7 as a function of the base layer thickness, where the measured values incidentaly fell on the Monte-Carlo simulation results.

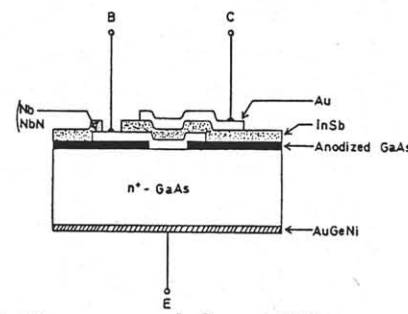

Fig.5 The prepared Super-HET.

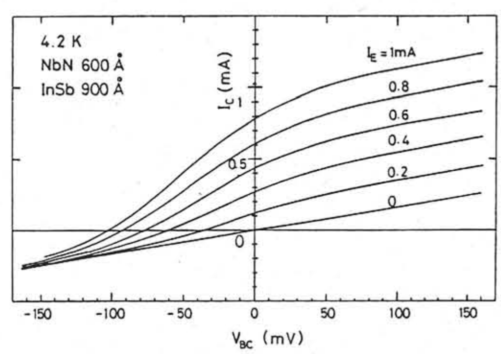

Fig.6 Transistor curve of the Super-HET.

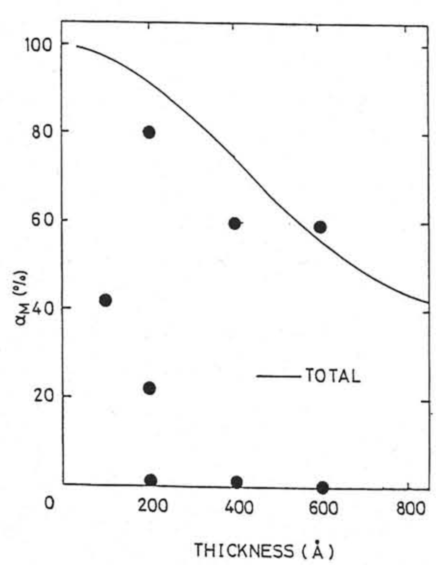

Fig.7 Observed amplification factor.

3-2. Key technology for improved Super-HET fabrication.

Very low reproducibility of the ideal Super-HET fabrication is thought to be due mainly to the intensive scattering of the injected quasi-particles during the transfer across the base layer. The dominant scattering in this stage might be with the micro-grain boundary involved in the base film very near the semiconductor interface and/or with the impurities coming into Nb (or NbN) film via alloying with the emitter material or in-diffusion of the constituent element (Ga and/or As) during the sputtering process. Especially at low temperatures, the electrons are subjected to more intensive interaction with both scatterers than others (phonon, electron-electron).

To overcome the above problem and get high yield of the excellent Super-HET, the substitution of the epitaxially grown MIS structure for the emitter-base portion is now under way. An introduction of a very thin insulating layer is believed to serve as the buffer layer for intermixture of the base and the emitter materials and also as the tunneling barrier providing the tunneling Schottky emitter. Moreover, if one uses MgO film as the insulator layer, the over-deposited NbN (Nb) will result in the epitaxial film.[14] Till now, we have obtained the epitaxially grown NbN films with (100) preferential orientation in the layer structure of NbN/MgO(20Å)/ Si, as shown in Fig. 8 by the X-ray diffraction data. Although the data are not given here, III-V compound materials were found to be likely to react even with the insulator MgO. The injection characteristics of the prepared emitter-base MIS structure are plotted in Fig. 9, exhibiting the satisfactorily good diode curves.

§4. Conclusions

A new hot-electron transistor "Super-HET" has been proposed and the preliminary experiment revealed that the Super-HET is capable of the efficient current amplifier. This device comprises the semiconductor-superconductor composite. Therefore, the possible epitaxial growth techniques will ensure the high reproducibility of the high quality Super-HET.

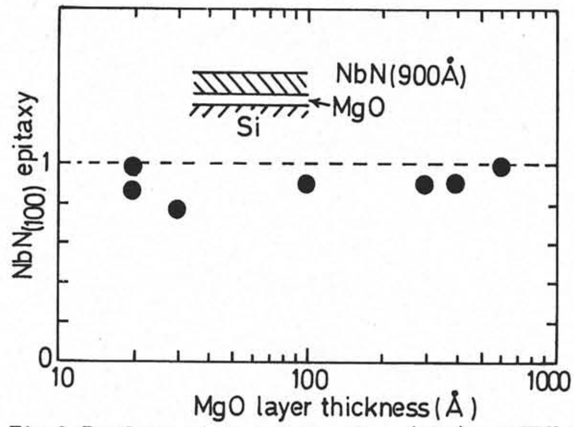

Fig.8 Preferential orientation (100) of NbN as a function of MgO thickness.

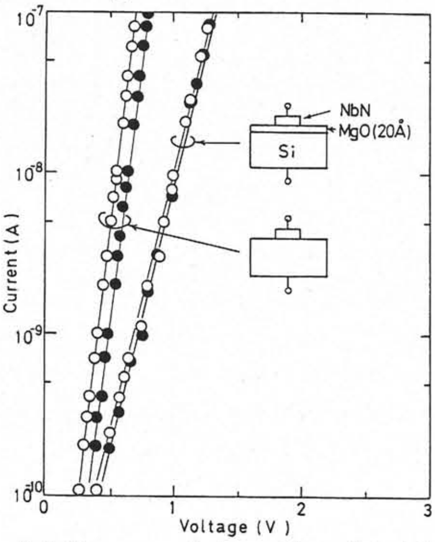

Fig.9 I-V curve of tunneling Schottky emitter.

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