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# Development of Cryogenic Enhancement-Mode Pseudomorphic High-Electron-Mobility Transistor Amplifier

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**Abstract** This paper reports the technical details of the development of a low-temperature amplifier for nuclear magnetic resonance measurements of superfluid $^3$He in very confined geometries. The amplifier consists of commercially available enhancement-mode pseudomorphic high-electron-mobility transistor devices and temperature-insensitive passive components with an operating frequency range of 0.2 to 6 MHz.

**Keywords** Superlfluid $^3$He · Superfluid $^3$He in Restricted Geometry · Low-Temperature Technique · Cryogenic Amplifier

**PACS** 67.30.H- · 67.57.-z · 84.30.Le

## 1 Introduction

Superfluid $^3$He in a narrow pore with a radius comparable to that of the p-wave Cooper pairs has attracted academic interest for several decades. Theoretically, the confinement of $^3$He in a long regular cylindrical channel greatly alters its phase diagram and reveals broken symmetry phases that are not observable in bulk $^3$He[1–3]. NMR experiments are essential to determine the phases of $^3$He. However, the NMR signal from $^3$He spins in such a narrow pore are too small to be detected by an ordinary passive detector. There are a few methods of overcoming this problem, the easiest of which is to bundle as many channels as possible. Using nematically ordered aerogel is the one of the impressive solution [4], but strong signal intensity is achieved at

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K. Obara
Department of Physics, Graduate School of Science, Osaka City University
Tel.: +81-6-6605-3672
Fax: +81-6-6605-2524
E-mail: obara@sci.osaka-cu.ac.jp

the cost of geometrical regularity. To avoid geometrical complexity, the use of a microfabricated cylinder with a regular shape to confine liquid $^3$He has been proposed; however, the filling factor of this method is very low because the signal intensity is proportional not to the number of spins in the volume surrounded by the receiving-coil but to the ratio of the volume of $^3$He spins within this volume to the total volume. Because the cylinder considered for use has a thick wall, the signal intensity does not increase even if the cylinders are bundled as tightly as possible. Therefore, other methods of increasing the signal intensity were adopted in this study. The first method is to increase the quality factor $Q$ of the resonator because in NMR measurements, the signal intensity is proportional to the quality factor $Q$ of the receiver coil. $Q$ is given by, $(1/R)\sqrt{L/C}$, where $R$ is the series resistance, $L$ is the self inductance, and $C$ is the total parallel capacitance. A high-sensitivity system can be realized using a high-$Q$ resonator containing a microfabricated superconducting coil. Additionally, because $C$ mainly consists of the capacitance of the coaxial cable $C_{\mathrm{coax}}$ and that of the variable capacitor in the tank circuit $C_{\mathrm{tank}}$, the distance between the sensor and the high-impedance amplifier must be as short as possible to minimize $C_{\mathrm{coax}}$. Introducing a low-temperature amplifier (LTA) can isolate the capacitance of the long coaxial cable from the sensor to the main amplifier which is located at the room temperature. There are five requirements for an LTA selected for use as a preamplifier for NMR. First, it is very convenient to keep the input impedance as high as possible to maintain an effective quality-factor of the resonator. The lower impedance amplifier can be easily made from the high impedance one. Second, the output impedance of the LTA must be as low as possible. Third, the LTA must be able to drive a long coaxial cable in the cryostat. Fourth, the frequency dependence of the gain must be flat in the NMR operating frequency region, which is approximately 1 MHz. Fifth, the energy consumption of the LTA must be as low as possible to operate the dilution refrigerator. For the present purposes, the gain of the LTA is not essential; however, too much gain increases the probability of an abnormal oscillation occurring.

Although superconducting quantum interference device (SQUID) amplifiers are the best choice of amplifier, additional techniques are needed to operate them, especially in the radio frequency (RF) range. Thus, constructing an easily operated conventional solid-state amplifier is still meaningful. This paper reports a process for producing an LTA with an operating frequency in the megahertz range.

## 2 Experimental

Although some metal–oxide–semiconductor field-effect transistors (MOSFETs) and full-complementary metal–oxide–semiconductor (CMOS) operational amplifiers are inexpensive and easy to operate even at temperatures at which $^3$He is liquid [5], their noise characteristics and gain bandwidth are poor. The thermal noise from the channel due to the finite resistance may be reduced by cooling. However, MOSFET noise is mainly caused by the carrier being randomly trapped in the layer of the oxide film below the gate contacts. This effect is inevitable and cannot avoided by cooling. Moreover, the resistance of the channel, which attenuates the high-frequency signal, cannot be reduced. Thus, MOSFETs are not the best choice to construct an LTA for relatively high-frequency experiments.

It is well known that high-electron-mobility transistor (HEMT) devices can be used to amplify a signal, such as a high-field NMR signal, an electron spin resonance (ESR) signal, or a microwave resonance signal. An HEMT is a field-effect transistor incorporating a junction between two materials with different band gaps, typically GaAs and AlGaAs. This heterostructure creates a quantum well in the GaAs side, and the carriers are generated from the thin n-type AlGaAs layer. Thus, the carriers in this quantum well can move quickly without colliding with any impurities, because the GaAs layer is undoped, enabling the device to function at high speeds. At low temperatures, the carrier densities of HEMTs are simply determined by the doping mechanism and thus negligibly depend on the temperature. Furthermore, the mobility of the electrons at high temperatures is affected by phonon scattering, which is reduced by cooling. It is important that there is no metal oxide layer isolating the gate contact from the quantum well to ensure that the generation of noise due to random carrier trapping never occurs.

Because of their noise characteristics and high performance at high frequencies, LTAs using metal–semiconductor field-effect transistors (MESFETs) have been developed for use in the field of the experimental cosmology [6]. The early stages of MESFET LTA development have been summarized by Kirschman [7]. The applications of LTAs in condensed matter physics began 10 years after their utilization in experimental cosmology [8, 9].

The temperature-independent term of the mobility, which is dominant at low temperatures, is determined from the electron scattering at the defects around the heterojunction resulting from the mismatch of the lattice constants. There are several techniques used to reduce the defects. The most popular technique is to make an extremely thin layer of AlGaAs. The transistors with this type of structure are called pseudomorphic HEMTs (pHEMTs). Recently, Oukhanski [10],and Neilinger [11] reported a sophisticated design using commercially available pHEMT devices, such as Avago ATF-34143. Intrinsically, pHEMT devices must be used in the depletion mode. However, enhancement-mode pHEMTs (e-pHEMTs) have recently been developed. This is very convenient from a design perspective because their circuit design is almost as same as that of a MOSFET, meaning that a negative voltage supply is not required. Using e-pHEMT devices may reduce the amount of electrical wire required in the cryostat. This paper focuses on LTAs with commercially available e-pHEMT devices for use in $^3$He NMR experiments at working frequencies of approximately 1 MHz.

In addition, it is important to use devices that are currently commercially available because the commercial life cycle of semiconductor devices is not very long; for example, the common transistor 3SK166 is no longer available.

For the present experiments, the e-pHEMT ATF-54143 (Avago Technologies) was selected.

## 3 Results and Discussion

First, the low-temperature characteristics of the passive components used to construct the LTA were examined. The frequency dependence of the thin-film resistors at 4.2 K was obtained, and the performance of the Susumu RR0816 and RR1220 families was found to be excellent. The frequency and voltage dependence of the ceramic capacitors at 4.2 K were also obtained. The TDK C1608C0G1H family of capacitors were found to negligibly change their capacitance in the target parameter space. The capacitance of the electrolytic capacitor was also obtained. The Vishay 293D Tantalum capacitors showed a weak temperature dependence; however, they can be used for decoupling purposes.

The dynamical response of the e-pHEMT devices was then measured at 4.2 K. Fig. 1 (left) shows a schematic of the test circuit, which is a conventional common-source amplifier. The right panel of Fig. 1 shows the actual design of the circuit board of our amplifier. The board glass-composite epoxy whose thickness is 1.0 mm. The green circle object located at the corner is the screw hole to make the better thermal conduction between the board ground and the cryostat. The size of our circuit board was 31.1 mm × 16.5 mm. The electrolyte capacitor $C_0$ and $R_{in}$ were not mounted on the board. The ground pattern was carefully designed to maximze its area. In this experiment, a high-impedance voltage probe was connected to the terminal labeled "SSout" in Fig. 1 (left). $R_1$ and $R_2$ define the gate bias voltage $V_\mathrm{g}$, which was approximately 0.23 V at room temperature and 0.46 V at 4.2 K. This bias voltage shift was due to the reduction of the thermally excited carrier. Once the amplifier is mounted on the cryostat, the only control parameter is the supply voltage $V_\mathrm{dd}$. $R_\mathrm{g}$ is the gate protection resistor that is needed to stabilize the FET (Q1 in Fig. 1). Additionally, $R_\mathrm{d1}$ and $C_\mathrm{d1}$ were included to achieve the optimal operating point. The e-pHEMT device can be operated in the same manner as a MOSFET. The optimum supply voltage was approximately 3.0 V. The corresponding drain current and total power consumption were 0.15 mA and 0.45 mW, respectively. The heating was not negligible for the dilution refrigerator; thus, it must be operated in a pulsed manner. In addition, this amplifier could be operated at room temperature by changing the supply voltage to 2.5 V. Next, the frequency dependence of the gain of the proposed single-stage amplifier was measured. The solid black symbols in Fig. 2(a) are the measurement results, which reveal the existence of two characteristic frequencies. The lower corner frequency was approximately 140 Hz, corresponding to the input filer structure. The dotted blue line in Fig. 2(a) is the theoretical curve given by

$$\mathrm{Gain} = G_0 \left\{1 + (2\pi f Z_\mathrm{in} C_\mathrm{in})^{-2}\right\}^{-1/2}, \tag{1}$$

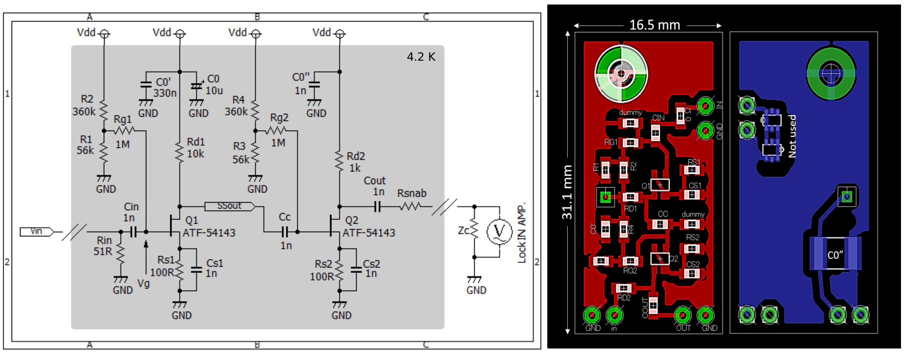


**Fig. 1** Schematic of single-stage amplifier. All parts in the hatched area are located in the cold (4.2 K) section of the device. All other parts are at room temperature. $R_{\text{in}}$ was included to match the impedance to that of the oscillator and thus must be removed to use this device as an actual preamplifier in NMR experiments. Actual design of the circuit board. Red and blue side indicate the top side and bottom side, respectively.

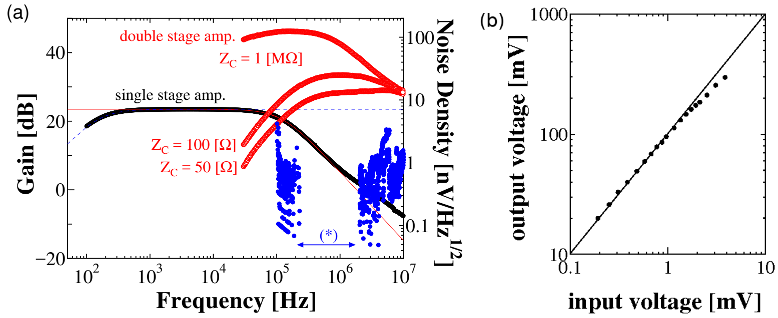


**Fig. 2** (a) Frequency dependence of the gain of the LTA at a temperature of 4.2 K. The solid black circles represent a single-stage amplifier with a supply voltage of 3.0 V and an input voltage of 30 mV. The solid red and blue dashed lines are the theoretical and best fit curves given by Eqs. (2) and (3), respectively. The open red circles represent the gain of the double-stage amplifier with a supply voltage of 3.3 V and an input voltage of 100 $\mu$V for three different impedances $Z_{\text{C}}$ of 50 Ω, 100 Ω, and 1 MΩ. Blue scattered symbols show noise density. See text for the blanked region, which was indicated with the asterisk (*). (b) Gain linearity of double-stage amplifier at 1 MHz. The solid line shows a linear gain of 40 dB. The input impedance of the lock-in amplifier was 1 MΩ.(Color figure Online)

where $Z_{\text{in}} = R_{\text{g}} + R_1R_2/(R_1 + R_2)$ and $G_0 = 14.93$. Additionally, the input impedance of this amplifier was revealed to be $Z_{\text{in}} + j2\pi f C_{\text{in}}$, which is approximately 1 MΩ. The higher corner frequency was approximately 100 kHz. This means that the low-frequency characteristics were determined by only the bias tee. The solid red line in Fig. 2(a) is the best fit curve, which is given by

$$\text{Gain} = G_0 \left\{1 + (2\pi f R_{\text{out}} C_{\text{eff}})^2\right\}^{-1/2}, \qquad (2)$$

where $f$ is the frequency, $R_{\mathrm{out}}$ is the output impedance, and $C_{\mathrm{eff}}$ is the effective capacitance of the load. Assuming $R_{\mathrm{out}} = R_{\mathrm{d}} = 10$ [kΩ], $C_{\mathrm{eff}} = 130$ [pF], which is a reasonable value for the practical capacitance of the coaxial cable.

The next objective of this study was to expand the bandwidth by reducing the output impedance, which can be realized by introducing a low-output impedance buffer. In principle, this buffer can be constructed using a source follower topology. A single-stage source follower was successfully produced, but it did not work well when connected directly to the SSout terminal because an abnormal oscillation occurred. Therefore, a double-stage common-source amplifier with a relatively low output impedance was constructed, as shown in Fig. 1 (left). The bandwidth and the gain peak can be tuned by selecting $R_{\mathrm{snab}}$ and $Z_{\mathrm{C}}$. Because the output frequency was not very low, the input impedance of the main amplifier had to be adjusted to an unconventional value. The open symbols in Fig. 2(a) show the measured gains of the double-stage amplifier at different impedances, revealing that the second-stage common-source amplifier greatly improves the high-frequency response. At large $Z_{\mathrm{C}}$, the maximum gain was nearly 10 times higher than that of the single-stage amplifier. The optimal $Z_{\mathrm{C}}$ was 100 Ω at $R_{\mathrm{snab}} = 0$, which was defined by the capacitance of the coaxial cable that connected the LTA to the main amplifier. The low-frequency characteristics were strongly limited by the introduction of the coupling capacitor, which had a capacitance of $C_{\mathrm{C}}$. The flat-gain region, which is also called the −3 dB band, extended from 0.2 to 6 MHz at the optimal settings. We also measured the noise density, which is plotted in Fig.2(a) with the blue dots. The blanked region, from 0.2 to 2 MHz, which was indicated with the asterisk (*), shows that the measured noise level fell below the measuring limit. The noise density of our LTA is lower than the conventional roomt-temperature-preamplifier, whose noise density is typically 1 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ at MHz range. These results mean that the amplifier is suitable for $^3$He NMR, because the frequency band corresponds to the static magnetic field from 6.5 to 30 mT. The ratio of the input voltage to the output voltage was also measured, as shown in Fig. 2(b). Gain linearity was achieved up to 1 mV input; this is not very high, but it is sufficient for use in NMR experiments.

## 4 Summary

The technical details of the development of an LTA for use as a preamplifier in $^3$He NMR in narrow pores were reported in this paper. The low-temperature characteristics of an e-pHEMT were also determined. An LTA with an input impedance is approximately 1 MΩ was ultimately successfully constructed, and its gain was more than 30 dB near the working frequency for $^3$He NMR.

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