Micro-Bubble Generation with Micro-Watt Power using Carbon Nanotubes Heating Elements

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***Abstract*—The generation of micro-bubbles using localized μwatt heating of Carbon Nanotubes (CNTs) is presented in this paper. Dielectrophoretic force is used to form CNTs between micro metal electrodes. The contact of the metal electrodes and the CNTs is fixed by a thin film of SiO_2. The localized heat generation by CNTs is provided by a DC current which induces a temperature increase due to resistive heating. The bubble diameter grew as the transduction of electrical energy into Joule-heating occurs continuously across the CNT heater. Similar to typical boiling phenomenon, the micron scale bubbles are generated using the CNTs as the nucleation site. Our experiments showed that the power required to generate bubbles was lower than ~113μW, which is only ~1 to 10% of the metal heaters as reported by other researchers. Experiments also showed that total input energy could be as small as ~2mJ to initiate bubble generation. As the maximum diameter of bubbles is around 100 microns and also the speed of the expansion of the diameter is controllable, this novel CNT heating element can be used in various application areas which require low energy consumption, such as hand-held ink-jet printing.**

Keyword: Nano-heaters; Micro-bubble generator; CNTs-heaters; Low-power Micro heater

I. INTRODUCTION

Micro heaters for bubble generation have been studied by various groups in recent years (Table 1). Different heating elements (e.g., Pt, polysilicon) were used as the heating source and nucleation site. For example, polysilicon was used as the heater by J.-H.Tai and L. Lin [1]. Then, Pt was formed to non-uniform and strip heater by P. Deng, et al., [2] [3]. The sizes of heaters have also become increasingly small. In the past five years, the dimension of heaters went from ~100um × 10um to ~1um × 0.5um. We note here that a typical 1um × 0.5um Pt heater will consume ~1.3mW for bubble generation, as have been demonstrated by P. Deng, et al., [2]. As CNTs show very unique characteristic of heat transfer, our motivation in this research endeavor is to see whether bubbles could be generated by lower power input. Our group has already shown the possibility of generating thermal bubbles with CNTs in 2006 [4] with ~0.4mW input power. In this paper we will show that with improved fabrication process, the power input requirement could be reduced further. We have also performed extensive experiments to understand the CNT-based bubble generation process.

II. EXPERIMENT PROCEDURE

A. Fabrication of the experimental device

CNTs are formed between the microelectrodes and used as the heater and nucleation site for bubble generation (see Fig 1). Silicon wafer is used as the substrate, and sputtered Cr and Au films are used to fabricate the electrodes. The CNTs are MWCNT bundles (diameter 10-30nm, length 1-5μm; Shenzhen Nanotech Port Co. Ltd., China). The gap between the electrodes is 5 microns, which allows formation of the CNTs by DEP force (-8~+8, 1MHz) [5]. In order to improve the contact of CNTs on the electrodes, a thin SiO_2 film is used to fix the CNTs and the electrodes [4] (see Fig 2). The SiO_2 also serves as an insulation film to prevent contact between the metal and DI water.

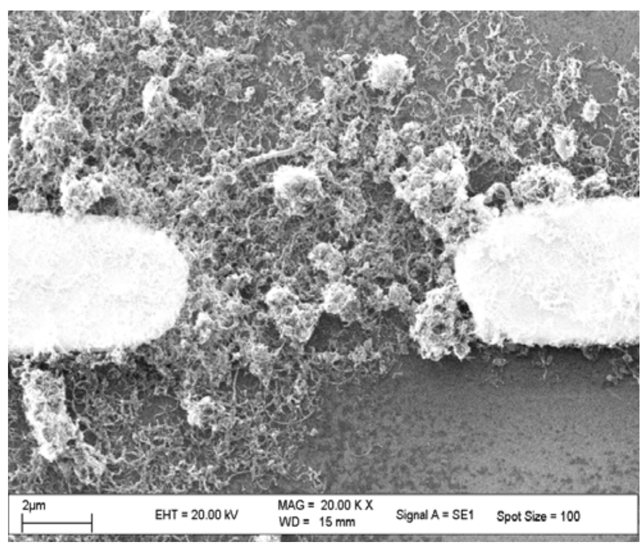

Fig 1: SEM Picture of a CNT Heater.

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Table 1: Comparison of power consumptions of various micro-heaters.

Research Group	Year	Input Signal	Power Consumption	Material& Resistance of Heater	Dimension of Heater
J.-H. Tsai & L. Lin, University of Michigan& U C Berkeley.	April 2002	DC	Minimum 187.3mW	Polysilicon 300 Ω	100um by 10um
P. Deng, et al., Hong Kong University of Science and Technology	April 2003	AC (pulse= 1.66ms)	Non-uniform heater 28.1mW	Pt 1.64 Ω /sq.	7um by 3um
			Strip heater 180.1mW		40um by 10um
P. Deng, et al., Hong Kong University of Science and Technology	March 2006	AC (pulse= 1.66ms)	Submicron heater 1.3mW	Pt 1.64 Ω /sq.	0.5um by 1um
			Micron heater 38.5mW		20um by 10um & 200um by 70um
W. Zhou, et al., The Chinese University of Hong Kong	January 2006	AC (100Hz)	Minimum 0.337mW	CNT 250 kΩ	5um by 5um

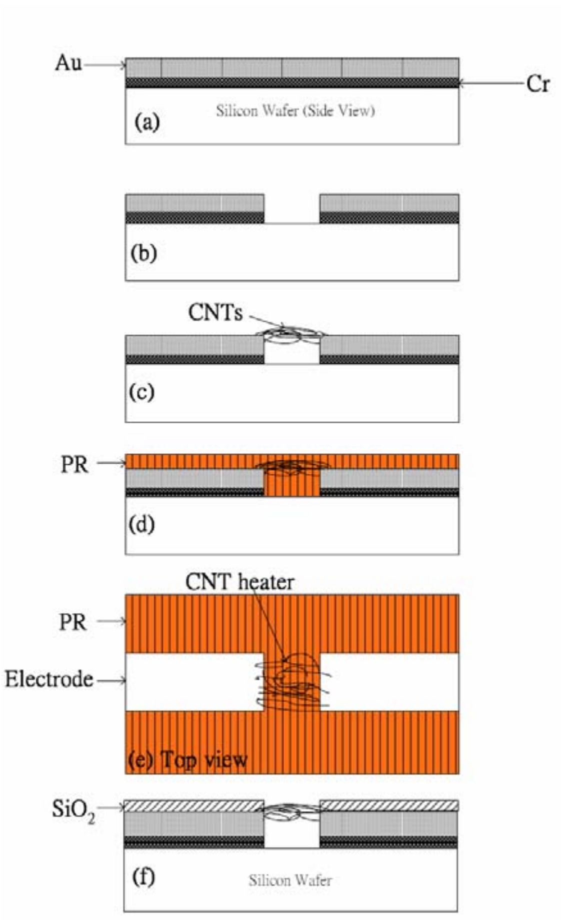

Fig 2: Fabrication process of the CNT Heater. (a) Metal deposition of Cr/Au. (b) Define electrodes by standard lithographic process. (c) CNTs formation by DEP. (d) Spin on PR and photolithographically define PR to cover CNTs. (e) Deposit SiO_2 and define SiO_2 by lift-off.

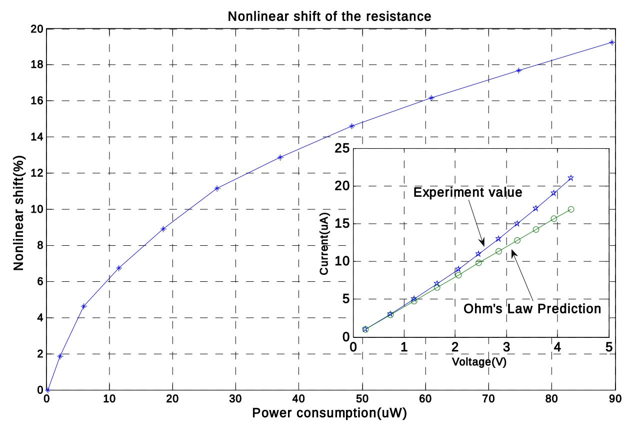

Fig 3: I-V characteristic and resistance nonlinear shift as a function of input power.

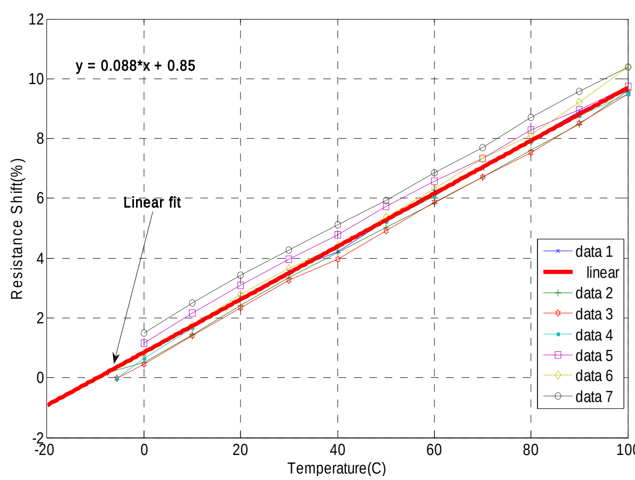

Fig 4: Temperature coefficient of typical a CNT resistor.

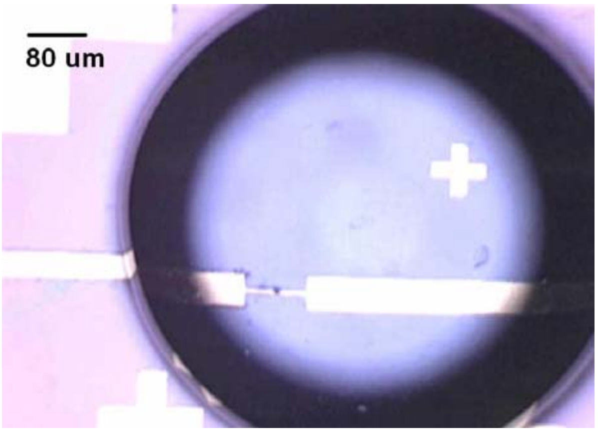

Fig 5: Static droplet of DI water on electrodes and CNT heating elements.

B. Initial analysis of the experimental device

The I-V curve of typical CNT heating elements was first recorded to understand the heating power characteristics of the micro heaters (see Fig. 3). As the power input increases, the nonlinear shift of the resistance increases simultaneously. From Fig. 3, nearly 19% change of resistance occurs when the power consumption is 90μW. Also, typical CNT heating elements (resistor) show linear resistance to temperature relationship. After testing a typical CNT heater 8 times in a programmable environment chamber, the initial value and slope of Temperature Coefficient of Resistance (TCR) remained stable (see Fig. 4). Hence, the temperature of a CNT heater at a given input power could be estimated by extrapolating from the resistance shift versus temperature relationship given in Fig. 4. Then, the CNT heating elements were covered by a diameter of 1500 microns droplet of DI water (25°C, 1ATM), to allow generation of bubbles in static condition (see Fig 5). 10μA was set as the initial current input, which requires ~120 seconds to generate bubbles. Meanwhile, the whole process was recorded by a high speed video camera at 30 frames/s. If no bubble was generated in this period, the current input was increased at 5μA intervals until a bubble was observed between the electrodes. The resistance data was also recorded every 0.7 seconds by an ADC when the current passed through the CNTs. The video of the bubble generation and the resistance data could be then analyzed synchronously.

The resistance of the CNTs between the electrodes is typically in the range of hundred to thousand kOhms. Due to a quite large resistance change at the gap of the micro electrodes, the amount of localized heat was generated at that small area between the electrodes.

Also, the resistance of CNT heater and equation of work integral $W = \sum_{t=0}^{t} P = \int_0^t (I^2 \times R)dt$ can be used to help determine the initial current input required for bubble generation. For example, based on the μW power requirement for bubble generation, if the resistance of a CNT heater is in the range of hundred kOhms, the initial current input should be set to 10μA; if the resistance is thousand kOhms, the initial current should be set to 3μA. Much higher current input may actually burn out the CNT heating elements.

The SiO_2 helps to improve the contact between the CNT and the gold electrodes. In our previous experiments without the SiO_2, internal circulation caused by convection depraves the connection between the CNT and electrodes. Also the non-conductor SiO_2 is a good insulator which means it helps concentrate heat on the CNT heater and prevents bubbles from generating on the surface of the metal electrodes.

We should note here that using the linear curve-fit relationship of

$$R_{shift}\% = 0.088T + 0.85 \qquad (1)$$

a ~19% change of $\Delta R / R$ in Fig. 4 is approximately equal to an estimated temperature change of ~209°C, with bubble generation required power consumption of ~90 μW. Hence, this is a proof that the temperature immediately around the CNT heater is above the boiling point of water, and such a high temperature should be able to stimulate nucleation on the CNTs.

III. EXPERIMENT RESULT

The bubble generation process is recorded by a high speed camera (see Fig. 6, 8). Before a bubble is generated, the CNT heater stores enough energy within a period of time to complete the phase change phenomenon. The time between the current input and bubble generation depends on the current and resistance of CNTs between the electrodes.

In this paper, two samples with detailed video pictures, schematic diagram of power consumption and work integral are shown for the bubble generation analysis. The initial resistance of first sample is 85kOhms, the second one is 156kOhms. The bubble generation current inputs are both 25μA. It takes 60.68s and 14.71s respectively for them to generate visible bubbles, corresponding to work integral of 0.006J and 0.00214J, respectively. The power consumption of these two samples is 87μW and 112μW, respectively (see Fig. 7,9).

We note here that in other research work (see Table 1), various groups have reduced the bubble generation power requirement by improving the heater material, heater size and shape, and the fabrication process. In our current work, we have shown that the CNT heater requires the least amount of energy input compared with materials used by others, i.e. Pt and polysilicon. The most obvious difference between these material is their resistance. Since $P = I^2 \times R$, the CNTs heater could induce large heat in a relative short time and localized area. So the efficiency of CNT heater is higher than other materials.

At the beginning of the bubble formation, the speed of bubble growth is fast. From Fig. 6 and 8, it takes 4.62s and 3.80s respectively for the bubble to grow to a diameter of nearly 60 microns. Then the growth rate is slowed down. That is because the surface tension becomes larger as the diameter of bubble grows. The bubble growth needs more energy to support it. Usually, if the current input is suspended, the growth will stop. Another reason could be the domination of viscous force of DI water at micro scale. This indicates that when the diameter of a bubble turns to be 60~100 microns, a bubble needs more vapor force to overcome the viscous force.

From the power consumption curves of both diagrams, a relative big change occurs on or a little before bubble generation. As $P = I^2 \times R$ and with constant current input, this actually is the resistance change during the bubble generation. After the liquid turns into vapor inside the bubble, the total resistance of media changes from $liquid + CNT$ to $liquid + vapor + CNT$. The resistance of DI water vapor is larger than that of DI water liquid. Also, before the bubble generation, the heat transfer in the droplet is natural convection. The localized heat flows upwards with the liquid while the cool liquid flows to surrounding of the CNT heater. Once a bubble is generated, the heat transfer turns to be forced convection and multi-phase flow. In that case, two procedures require more energy input. This can well explain the jump in power change when bubble appears.

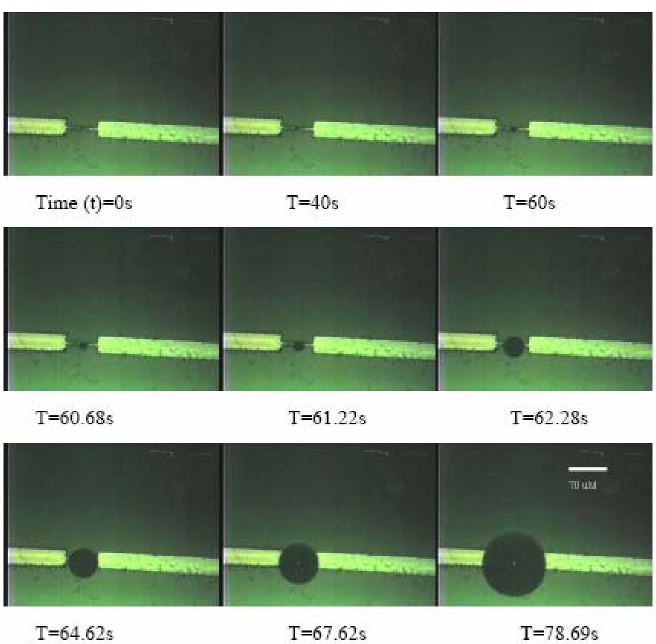

Fig 6: Time-sequence photos of a bubble generated by a CNT heater (current input=25ua; initial resistance=85K Ω).

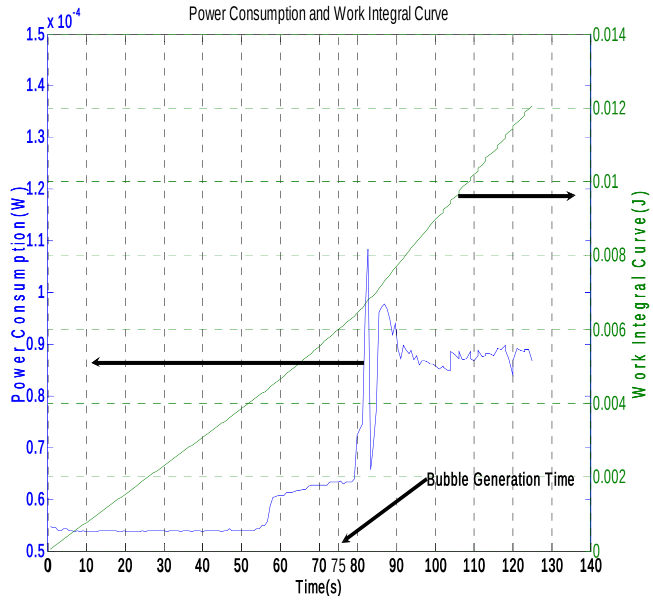

Fig 7: Power variation and work integral across a CNT heater (initial resistance is ~85kOhm) as a bubble is generated. (Power is calculated by P=IV, where I is set to 25 μA, while V is increased versus with time.)

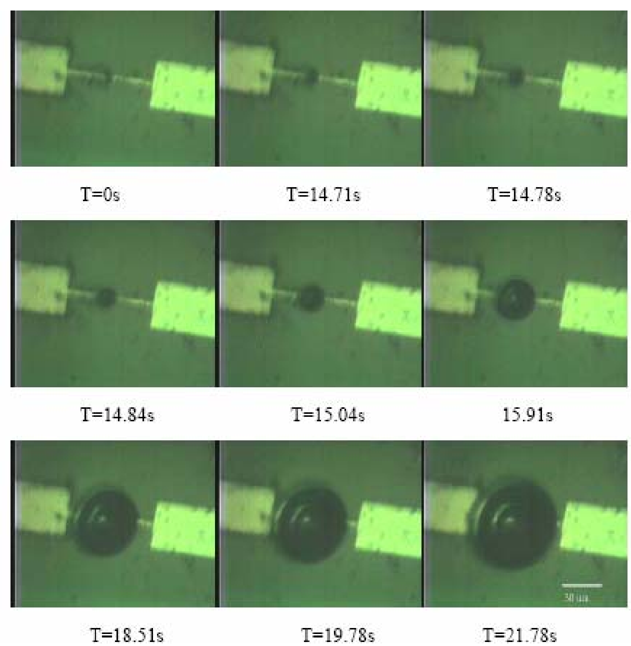

Fig 8: Time-sequence photos of a bubble generated by a CNT heater (current input=25ua; initial resistance=156k Ω).

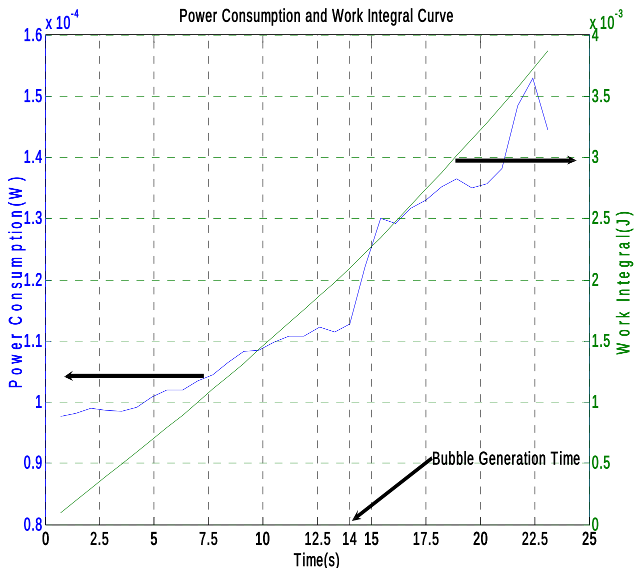

Fig 9: Power variation and work integral across a CNT heater (initial resistance is ~156kOhm) as a bubble is generated. (Power is calculated by P=IV, where I is set to 25 uA).

After analysis of various CNT heaters with detailed videos, other experiment results are also shown below. The current input, initial resistances, time for bubble generation are varied. We have observed that following results from these experimental work. Referring to Fig. 10, the bubble generation time is at 48s and 17s, which is because the resistance of them is different. Also, an obvious *power consumption jump* happens around the bubble generation time. Another conclusive statement is that the higher the CNT resistance, the quicker the bubble generation (Fig 11), i.e., smaller work-integral is required. This is because a greater localized heat makes the phase change faster. These experiments have also shown the maximum power consumption for bubble generation using the CNT heaters we have fabricated is 113μW, and the work integral is around 0.3~5mJ. After the bubble generation, the resistance keeps increasing slowly or stays in a stable range. This indicates that main power consumption is induced by phase change and different heat transfer phenomenon.

IV. CONCLUSION

After improving the fabrication process from our prior work, the bubble generation on CNT heaters can now be very repeatable and requires less input energy. With experiment analysis, the power consumption is controlled to be under 113μW and work input is around 0.3~5mJ. Also, from the work integral curve (see Fig 11), the larger

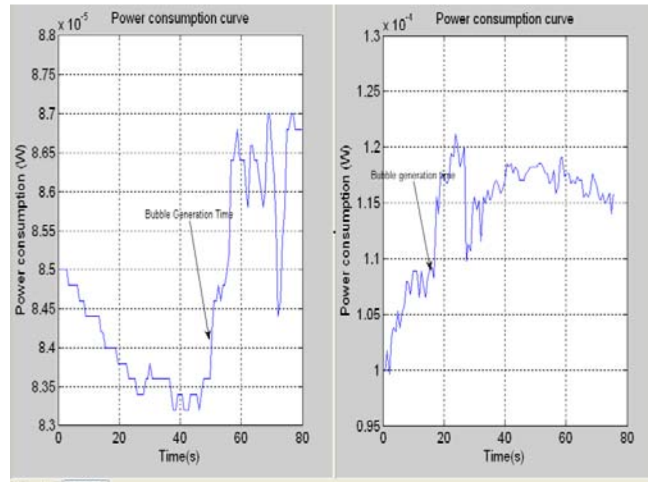

Fig 10: Power variation across the CNTs heater as a bubble is generated on different samples.

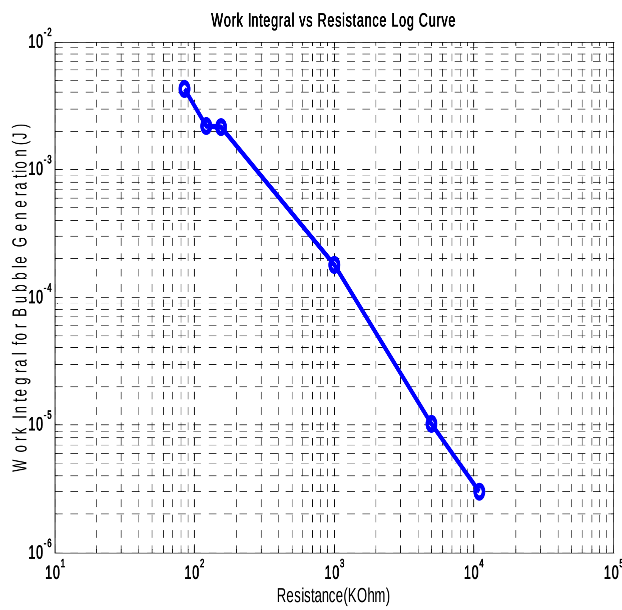

Fig 11: Work integral required for bubble generation as a function of initial heater resistance

the resistance, the lower the work integral is observed.

As the bubble generation can be well achieved by a single pair electrode, inter-digitated electrodes will be used in the future to explore various applications of the CNT generated bubbles. Meanwhile, the static DI water droplet will be changed to a dynamic microchannel fluidic system to study the bubble transport process.

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