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Cu Nanostructures for Enhanced Heat Transferin Micro Systems

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Abstract

Vertically aligned copper (Cu) nanorod arrays fabricated by glancing angle deposition (GLAD) technique was used to study the heat transfer by natural convection in micro systems. These nanorods were deposited on Cu thin film surface, which was coated on Si (100) wafer substrates. For comparison, planar Cu thin film samples were also produced by normal incidence deposition. This study focuses on investigating experimentally the heat transfer by natural convection from the sample (nanostructured plate) to the surrounding air. Newton's lawof cooling has been utilized to calculate thefree-convection heat transfer coefficient for Cu nanorods as well as Cu thin film. Compered to Cu thin film samples, it has been found that the heat transfer coefficient values of Cu nanorods are higherdue to the enhanced heat transfer-surface area, which causes a significant reduction in thermal resistance. These nanostructured surfaces offer an effective method of device cooling such as for small electronic devices, micro-reactors and air conditioning.

أعمدة النحاس النانوية لتحسين انتقال الحرارة بالحمل الحر في الأنظمة الميكروية

الملخص:

تم تصنيع أعمدة النحاس النانوية بطريقة Glancing Angle Deposition (GLAD) بأطوال مختلفة (٢٠٠، ٤٠٠، ٦٠٠ نانو متر) لدراسة انتقال الحرارة بالحمل الحر في الأنظمة الميكروية. حيث تم ترسيب أعمدة النحاس النانوية على صفائح السيلكون الرقيقة والتي تم ترسيب طبقة رقيقة جدا من النحاس عليها لتعمل كمادة موصلة بين اعمدة النحاس النانوية. للمقارنة تم تصنيع اغشية النحاس الرقيقة بسمك (٢٠٠، ٤٠٠، ٦٠٠ نانو متر) على صفائح السيلكون الرقيقة ايضا. تم استخدام قانون نيوتن لحساب معامل انتقال الحرارة بالحمل الحر للنماذج المصنعة. بينت النتائج ان أعمدة النحاس النانوية أظهرت تحسن بانتقال الحرارة من خلال قيم معامل انتقال الحرارة العالية مقارنة مع اغشية النحاس الرقيقة. هذا البحث أوضح ان صفائح النحاس النانوية تعتبر أحد طرق التبريد المهمة في العديد من التطبيقات مثل الأجهزة الالكترونية الصغيرة والمفاعلات الميكروية واجهزة التبريد والتكييف.

Introduction

The rapid increase in heat dissipation power of microprocessors and microchips is closely linked to the ability of the heat transfer community to facilitate the development of ultra-low thermal resistance heat sinks.In addition tothe cooling for small electronic devices,many other applications such as air-conditioning, biotechnology, fuel cells, micro-propulsion, and micro-reactor utilized the technology of micro heat sink [1]. There is a great interest in enhancing the removal rate of heat, which promotes the need of studying the heat and fluid flow in micro scale. In order to achieve high heat transfer performance, many studies were carried out [1-8]. In these studies,Cu nanorod arrays, fabricated by glancing angle deposition (GLAD)technique, were employed due to their positive effect on heat transfer coefficients with diminishing length scale and in increasing the surface area available for heat transfer.The GLAD technique offered a novel capability in fabricating metallic nanorod arrays, whichdemonstrated a great potential in different applications such as energy [9] and heat transfer fields [1-8] due to their unique physical and chemical properties such as formation of uncommon crystal planes and single-crystal property.

Motivated by the positive results of these nanorods in water cooling/boiling systems [1-8], this is in addition to the fact that there is physical limitations in achieving the required air cooling performance caused by the limited thermal conductivity of copper (Cu) for conduction and air for convection, it is encouraging to examine heat transfer by natural and forced convection on these nanostructures.To the knowledge of the author, there is no work done in which the glancing angle deposited Cu nanorods were utilized for natural and forced convection heat transfer applications. The closest experimental research work was performed by depositing the Cu nanoparticles onto a heat sink to investigate the heat transfer by the means of natural and forced convection [10].For natural convection, the results revealed that there is 6% heat transfer enhancement for the nanostructured surface heat sink compared to the conventional heat sink, while the forced convection results showed approximately negligible difference as the air velocity increases [10].

The nanoscale science and technology offers new opportunities to develop novel nanostructuredheat sinks with dramatically improved heat transfer performance. Therefore, as preliminary results, the aim of this project is to study the heat transfer by natural convection on compact nanostructured heat sink based on copper nanorods.The Cu was selecteddue to its favorable properties, whichattracted a great potential in several branches of industries.

Three-dimensional nanostructures with interesting material properties can be produced utilizing the glancing angle deposition (GLAD) technique, which is also called oblique angle deposition.The GLAD technique is a simple, single-step, and cost and time efficient for fabricating nanostructured surfaces of various materials (pure elements, compounds, alloys, and oxides) [11-

15]. It usesthe "shadowing effect" which a physical self-assembly growth technique,which promotes the preferential growth on the islands of higher height on the substrate. During GLAD deposition, some islands grow faster in the vertical direction, allowing them to capture the obliquely incident atoms, while the shorter islands get shadowed and cannot grow any more, leading to the formation of isolated nanostructures. These nanostructures have interesting properties such as high thermal/electrical conductivity and single crystal property that reduces surface oxidation in comparison with the polycrystalline films [11-15].

In this work, a systematic study is carried out by fabricating the nanostructured plates(Cu nanorods deposited on silicon substrates)with different nanorod lengthsof 200, 400, and 600 nm. For comparison of heat transfer performance, Cu thin filmsserving as referencesamples are also prepared with different thickness of 200, 400, and 600 nmon silicon substrates.

1. Experimental Work

1.1 Nanofabrication

Figure 1 demonstrates the schematic of the GLAD setup (Excel Instruments, India) which was used to grow vertically aligned Cu nanorod arrays. The Cu nanorods of different lengths (200, 400, and 600 nm) were deposited at a glancing angle of θ = 87° (with respect to the substrate normal) on about 50 nm thick flat Cu thin layer, which serves as a conducting layer, coated 3.6 mm thick silicon (100) substrates.The substrates were rotated around the surface normal with a speed of 2 rpm. The distance between the substrate and the sputter target (99.9% pure Cu cathode disk-shaped source with 7.6 cm in diameter) was approximately 12 cm. In order to achieve a base pressure of 5 x 10^{-7} Torr, a turbo-molecular pump backed by a mechanical pump were used. During GLAD deposition, a DC power supply was employed to generate the plasma for the Cu target with a power of 200 W and an ultra-pure Argon working gas pressure of 2.4 x 10^{-3} Torr. The substrate maximum temperature was below 85 ^{o}C during growth. On the other hand, the Cu thin films of different thickness (200,400, and 600 nm) by normal incidence deposition ($\theta = 0^{o}$) with a substrate rotation of 2 rpm were also prepared to be compared with their counterparts Cu nanorods.

The morphology of Cu nanorods as well as Cu thin films was evaluated by scanning electron microscopy (SEM) unit (FESEM-6330F, JEOL Ltd, Tokyo, Japan).The quartz crystal microbalance (Inficon- Q-pod QCM monitor, crystal: 6 MHz gold coated standard quartz) measurements as well as the analysis of the SEM images were utilized to calculate the deposition rate of the GLAD Cu nanorods to beapproximately~8.6 nm/min.By controlling the deposition rate and time, the length of the rods can be set to values from a few nanometers up to the micrometer range.

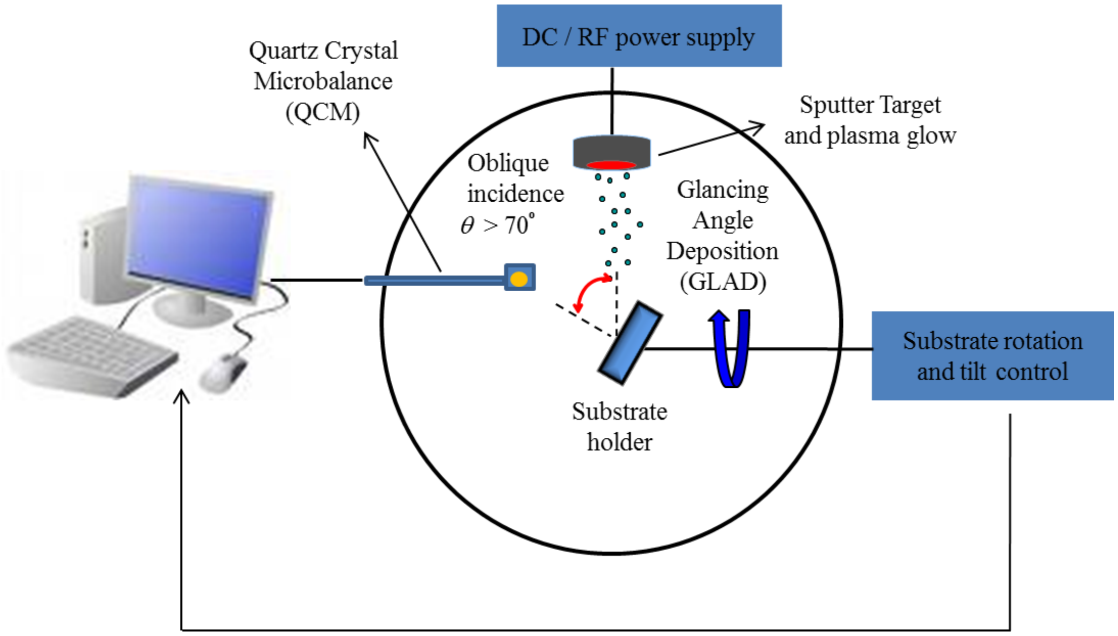

Figure 1: A schematic of the glancing angle deposition (GLAD) technique used for the fabrication of nanorod arrays is shown.

1.2 Heat Transfer Setup

The heat transfer experimental setup is shown in Fig.2. The experimental setup includes aluminum bar with a geometric surface area of (4 cm^2) as a base for placing our samples on it, a heater that is located underneath the aluminum bar to provide a constant heat flux (200 W/m^2) to the system. The heater is treated with thermal grease for smooth contact with aluminum bar. The Cu thin film and Cu nanorods samples were placed on the aluminum bar, which were also treated with thermal grease. Thermocouples were placed on the heater surface, aluminum bar surface, and Cu thin film and nanorods surfaces at different places for the accurate measurement of the surface temperature. The aluminum bar and the heater regionswere thermally insulated to assure nearly one-dimensional thermal conduction, therefore, the heat is directed from the heater to aluminum bar and then to the samples. In our experiments, the heat transfer by conduction from Al bar to the samples and then by natural convection from the samples to the surrounding air, which was investigated experimentally.The experimental heat transfer data are listed in Tables 1-6 as shown in Appendix A.

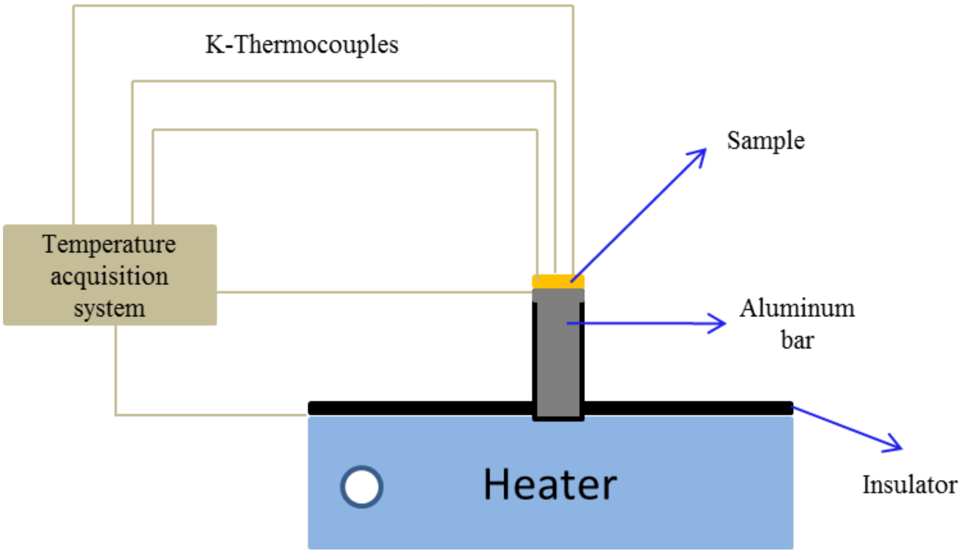

Figure 2: A schematic of the heat transfer experimental setup.

4. Results and Discussion

4.1 Surface morphology: SEM measurements

Figure 3 shows the top ad side view SEM images of vertically aligned Cu nanorods of different lengths (200, 400, and 600 nm). The isolated columnar morphology of the nanorods can be clearly seen from the SEM images. While Cu thin film samples of different thickness (200, 400, and 600 nm) exhibit a smooth morphology as shown in Fig.4. It should be noted the number density of the nanorods was large at early stages of GLAD deposition. The diameter of these nanorods as small as 5-10 nm. Due to the shadowing effect, some get longer and wider (the nanorod diameter may reach 100 nm), while others stop growing. At later stages of GLAD deposition, the space among the nanorods also changes with their lengthand diameter from 5-10 up to 50-100 nm.

The careful examination of the SEM images of the nanorods in Fig. 3 reveals that some of the nanorods have 6-fold symmetric faced tips, indicating that an individual nanorod has a single crystal structure. This observation is in a good agreement with previous studies [9, 16]. The faceted sharp tips as well as the absence of the interior grain boundaries of the nanorods are expected to reduce the surface oxidation and thus increasing the thermal conductivity and robustness.

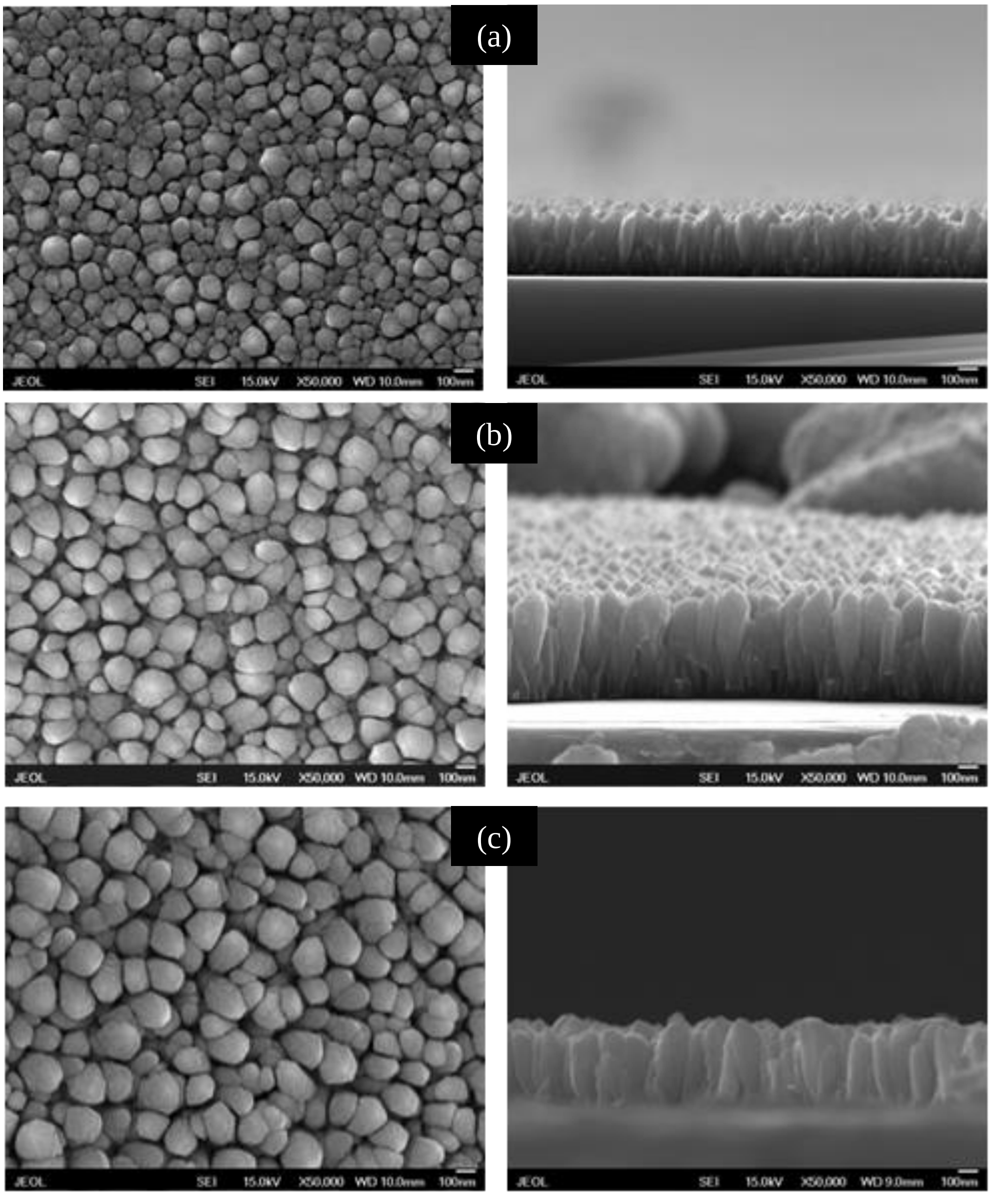

Figure 3: Top and cross-section scanning electron microscopy (SEM) views of GLAD Cu nanorod arrays grown at lengths of (a) ~200, (b) ~400, and (c) ~600 nm are shown.

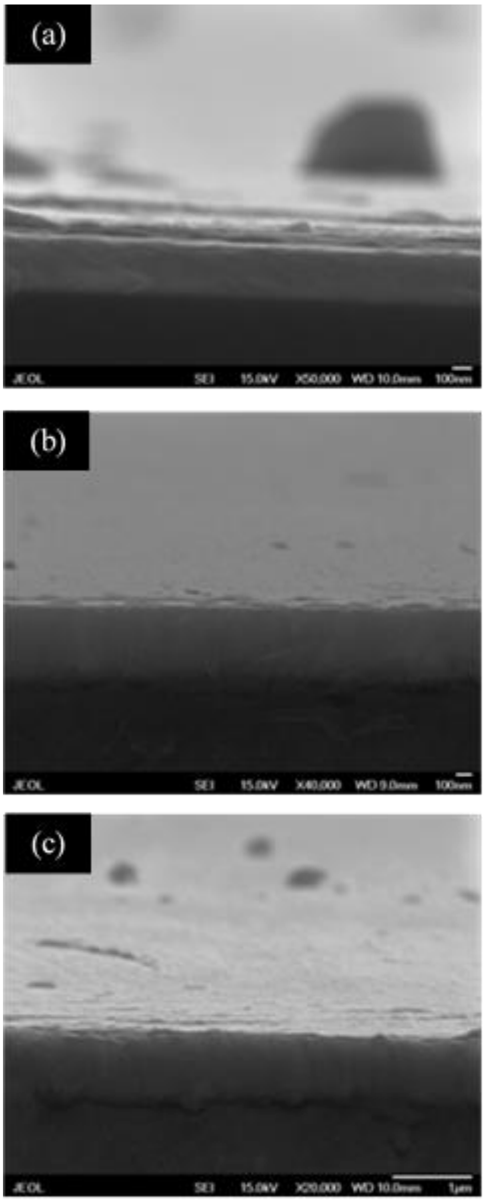

Figure 4: Top and cross-section scanning electron microscopy (SEM) views of Cu thin films grown at thickness of (a) ~200, (b) ~400, and (c) ~600 nm are shown.

4.2 Heat Transfer Measurements

Figures 5 and 6 show the temperature change of both the surface of samples (Cu thin films and nanorods) and the Al bar surface. It can be clearly seen that as the thickness of Cu thin film increases, the heat transfer increases; the heat removal of Al bar surface, which is considered as a surface of the microsystem, is enhanced.The same trend has been found on the Cu nanorods as the length of the nanorods increases from 200 nm to 600 nm. However, the Cu nanorods samples demonstrate higher heat transfer removal (enhanced cooling of the Al bar surface) than Cu thin films.

The enhanced heat transfer rate over Cu nanorods can be reflected by calculating the heat transfer coefficients for both Cu thin films and Cu nanorods samples. First, the heat flux provided to the system ($\dot{q}$) is obtained from the following equations:

$$\dot{q} = \frac{P}{A}$$

Where P is the input power supplied by the heater and A is the heated surface area of the plate. Then the heat transfer coefficient, h, can be calculated from the following equation:

$$h = \frac{\dot{q}}{T_s - T_a}$$

Where T_s is the surface temperature of the sample and T_a is the average fluid (air) temperature.

Table 1 summarizes the heat transfer coefficient values of the Cu thin film and Cu nanorods samples. The heat transfer coefficients are calculated to be 5.8, 5.7, and 5.7 W/m^2. K for 200, 400, and 600 nm thick Cu thin films, respectively. While the 200, 400, and 600 nm long Cu nanorods exhibit highervalues of 8.3, 8.5, and 9.5 W/m^2. K, respectively.The enhanced heat transfer rate on Cu nanorods is due to the increasedsurface area of heat transfer and enhanced heat transfer coefficients caused by the diminishing length scale of the Cu nanorods. This is an encouraging result, which motivates us to continue working on investigating the heat transfer by forced convection on the Cu nanostructures for microsystem applications.

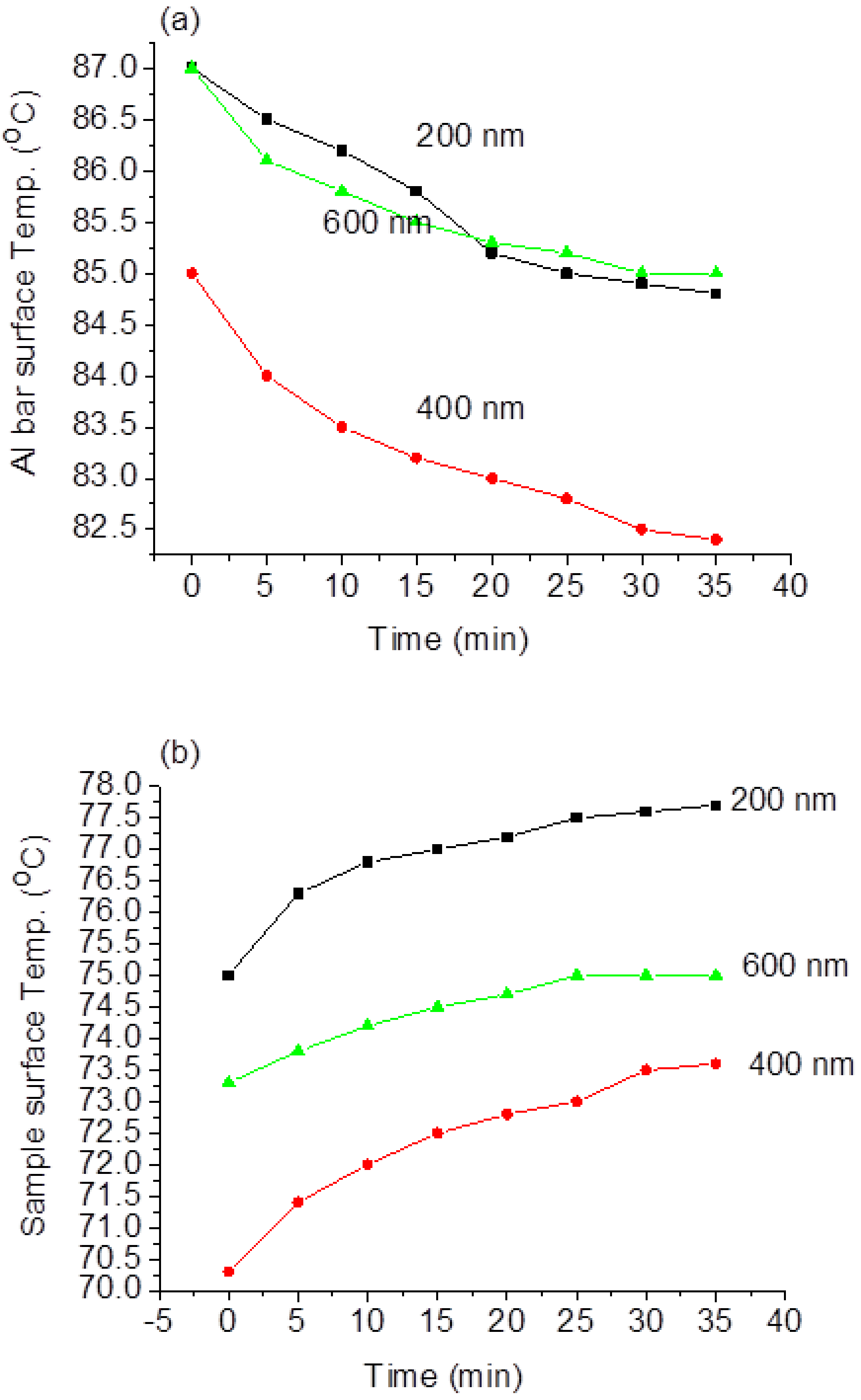

Figure 5: Heat transfer by natural convection (a) Aluminum bar surface temperature vs. time and (b) Cu thin film surface temperature vs. time

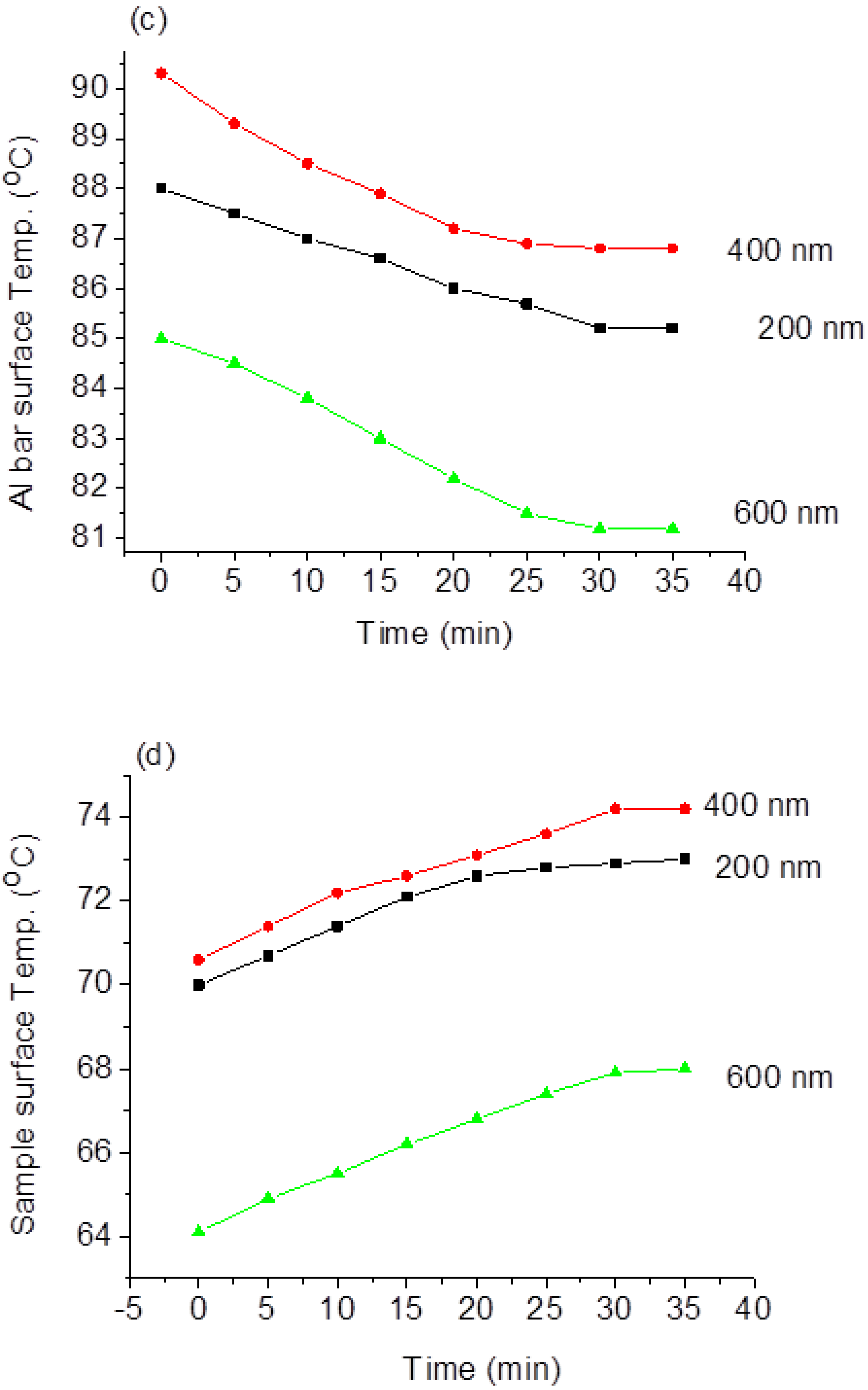

Figure 6: Heat transfer by natural convection (c) Aluminum bar surface temperature vs. time and (d) Cu nanorods surface temperature vs. time.

Table 1: Heat transfer coefficient (*h*) values for natural convection on Cu thin film and Cu nanorods samples.

Sample	*h* (W/m^2. K)
200 nm Cu thin film	5.8
400 nm Cu thin film	5.7
600 nm Cu thin film	5.7
200 nm Cu nanorods	8.3
400 nm Cu nanorods	8.5
600 nm Cu nanorods	9.5

5. Conclusion

An efficient air-coolingsystem, which consists of vertically aligned Cu nanorods, produced by glancing angle deposition (GLAD) technique on Cu thin layer, which was coated on Si substrates, a heater, and Al bar was developed. The nanostructured plate (Cu nanorods) increases heat removal from the system more efficiently compared to the Cu plain surface due to the enhanced surface area available for heat transfer and diminishing length scale of Cu nanorods, whichhave a positive effect on heat transfer coefficients. The anticipated impact of the proposed research will provide the heat transfer community with an innovative engineering tool to establish next generation of air cooling technology in microscale, which will provide cooling solutions to futuristic ultra-high power dissipating electronic microprocessors, microchips, and ultra-compact heat exchangers. These resultswill encourage us to continue this project by investigating the heat transferby forced convection, which is more practical than natural convection, on Cu thin film as well as Cu nanorods.

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Appendix A: Experimental Heat transfer data

Table 1: Heat transfer data by natural convection of 200 nm thick Cu thin film sample

Time (min)	Heater surface Temp. (^{o}C)	Al bar surface Temp. (^{o}C)	Sample surface Temp. (^{o}C)	Air Temp. (^{o}C)
0	200	87	75	40.5
5	200	86.5	76.3	41.2
10	200	86.2	76.8	41.8
15	200	85.8	77	42.5
20	200	85.2	77.2	42.8
25	200	85	77.5	43.1
30	200	84.9	77.6	43.3
35	200	84.8	77.7	43.3

Table 2: Heat transfer data by natural convection of 400 nm thick Cu thin film sample

Time (min)	Heater surface Temp. (^{o}C)	Al bar surface Temp. (^{o}C)	Sample surface Temp. (^{o}C)	Air Temp. (^{o}C)
0	200	85	70.3	35.6
5	200	84	71.4	36.5
10	200	83.5	72	37.2
15	200	83.2	72.5	37.5
20	200	83	72.8	38.2
25	200	82.8	73	38.5
30	200	82.5	73.5	38.8
35	200	82.4	73.6	38.8

Table 3: Heat transfer data by natural convection of 600 nm thick Cu thin film sample

Time (min)	Heater surface Temp. (^{o}C)	Al bar surface Temp. (^{o}C)	Sample surface Temp. (^{o}C)	Air Temp. (^{o}C)
0	200	87	73.3	36.8
5	200	86.1	73.8	37.6
10	200	85.8	74.2	38.2
15	200	85.5	74.5	38.8
20	200	85.3	74.7	39.4
25	200	85.2	75	39.8
30	200	85	75.1	40
35	200	85	75	40

Table 4: Heat transfer data by natural convection of 200 nm long Cu nanorod sample

Time (min)	Heater surface Temp. (^{o}C)	Al bar surface Temp. (^{o}C)	Sample surface Temp. (^{o}C)	Air Temp. (^{o}C)
0	200	88	70	45
5	200	87.5	70.7	46.2
10	200	87	71.4	47
15	200	86.6	72.1	47.7
20	200	86	72.6	48.3
25	200	85.7	72.8	48.7
30	200	85.2	72.9	49
35	200	85.2	73	49

Table 5: Heat transfer data by natural convection of 400 nm long Cu nanorod sample

Time (min)	Heater surface Temp. (°C)	Al bar surface Temp. (°C)	Sample surface Temp. (°C)	Air Temp. (°C)
0	200	90.3	70.6	46
5	200	89.4	71.4	46.9
10	200	88.5	72.2	47.8
15	200	87.9	72.6	48.6
20	200	87.2	73.1	49.5
25	200	86.9	73.6	50.2
30	200	86.8	74.2	50.8
35	200	86.8	74.2	50.8

Table 6: Heat transfer data by natural convection of 600 nm long Cu nanorod sample

Time (min)	Heater surface Temp. (°C)	Al bar surface Temp. (°C)	Sample surface Temp. (°C)	Air Temp. (°C)
0	200	85	64.1	41.4
5	200	84.5	64.9	42.6
10	200	83.8	65.5	43.7
15	200	83	66.2	44.6
20	200	82.2	66.8	45.7
25	200	81.5	67.4	46.5
30	200	81.2	67.9	47
35	200	81.2	68	47