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COOLING SYSTEM OF SEMICONDUCTORS WITH BOILING CHEMICAL LIQUID

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I. INTRODUCTION

Recently, power semiconductor capacity has increased so rapidly that it has exceeded 800 amps. As large capacity power semiconductors mentioned above give out much heat loss, over 1kw (860 kcal/hr), for their junction of only a few cm^2, cooling has become very important.

Conventionally, air, water or transformer oil have been used as coolants in power semiconductors. Of these three, air provides the most simple cooling structure but the cooling capacity is limited and the noise caused by the cooling fan often presents a problem. Water is excellent regarding heat transfer, but poor regarding electrical insulation. Therefore it is only used for low voltage applications such as electrolysis service with ion exchange resin. Transformer oil is not an ideal coolant for heavy power semiconductors, because it has poor heat transfer, about one tenth compared to water; however, it has excellent electrical insulation.

In contrast to these coolants, chemical coolants such as FC 77 (fluorochemical liquid) or Freon have good electrical insulation characteristics and when they are used in the boiling state, their heat transfer coefficients reach values of 2000$\sim$7000 kcal/m^2·hr·deg as can be seen from *Fig. 1*. These values are extremely large when compared with the 100 kcal/m^2·hr·deg obtained with forced air convection.

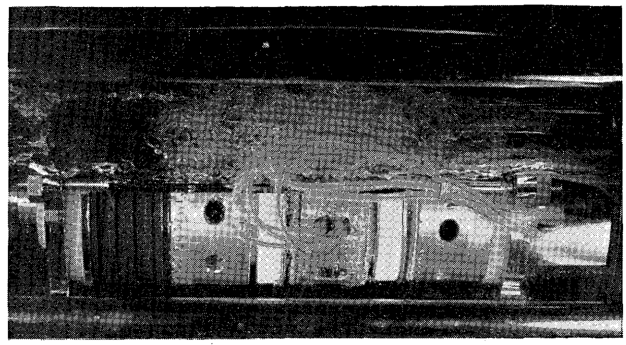

Fig. 2 Cooling condition of boiling in model equipment

Fig. 2 is a photograph showing the condition of cooling disk type semiconductors with boiling chemical liquid at model set. With this method, very effective cooling is achieved because the heat loss is eliminated directly as bubbles by means of the latent heat of evaporation.

This article will describe the basic techniques of semiconductor cooling using chemical liquids in the boiling condition. The discussion is concerned mainly with the results of tests with Freon. (For further information, refer to the article concerning rectifier equipment using boiling Freon cooling in this issue).[1]

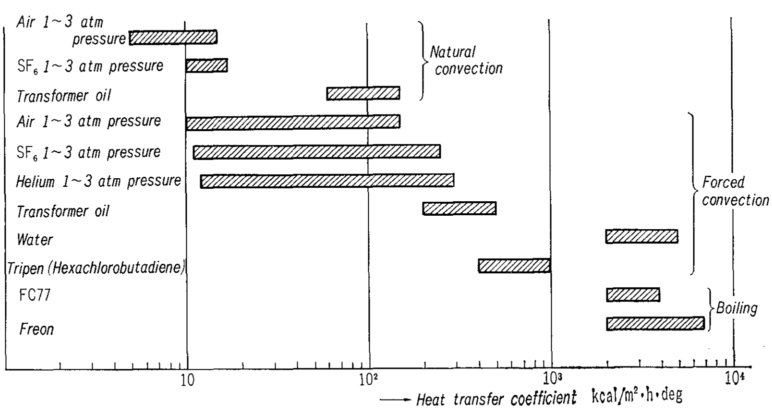

Fig. 1 Heat transfer coefficients for different coolant

II. CHEMICAL COOLANTS AND THE BOILING-TYPE COOLING SYSTEM

Typical chemical coolants are tripen (hexachlorobutadiene), FC 77 (fluorochemical liquid), Freon etc. *Table 1* contains the main characteristics including physical values for these chemical coolants, as well as for water and transformer oil.[(2)(3)]

Tripen is the brand name of hexachlorobutadiene. It is used with forced convection like transformer oil and the heat transfer coefficient is 400∼1000 kcal/m²·hr·deg or about twice that of oil.

FC 77 and Freon can be used for boiling and have very high heat transfer coefficients. FC 77 is a brand name of fluorochemical liquid marketed by the Minnesota Mining and Manufacturing Co. In the same series are FC43, FC75 and FC78 ; all of which have different boiling points. Freon is used in refrigerating machinery etc. and is manufactured by the Kinetic Chemical Co. (now merged with Du Pont). In Japan, it is known as " Flon ".

The principles of boiling-type cooling using these coolants is as follows. As mentioned previously, the cooling system is a very serious problem in semiconductors etc. where there is considerable heat loss from a small area. The so-called boiling chemical liquid method is highly effective in such cases. As shown in *Fig. 3*, the semiconductor etc. to be cooled is placed in the lower part of a sealed case and enough liquid coolant to immerse the body to be cooled is inserted in the case. In the top part of the sealed case, there is a space for vaporized coolant and a heat exchanging section for condensation of the coolant vapor. If forced air cooling is used, for example, the heat exchanging section consists of a suitable heat exchanger attached in the vapor space or fins to provide sufficient cooling area. Since complete electrical insulation is provided by the chemical coolant, this equipment can be used as a heat exchanger in such applications as water cooling pipes which directly employ standard factory water with low insulation characteristics. The heat loss from the semiconductor is absorbed directly by the boiling coolant. The vaporized coolant rises in the case and is condensed in the heat exchanger section where the heat radiates to the exterior. The heat transfer coefficiient of the heat exchanger section where the heat radiates to the exterior is naturally low when compared to the heat transfer coefficient due to boiling, but the temperature difference between the two can be kept low because of the large cooling area in the heat exchanger section. With this type of boiling/condensation cycle, the heat loss from a small area can be absorbed for effective cooling.

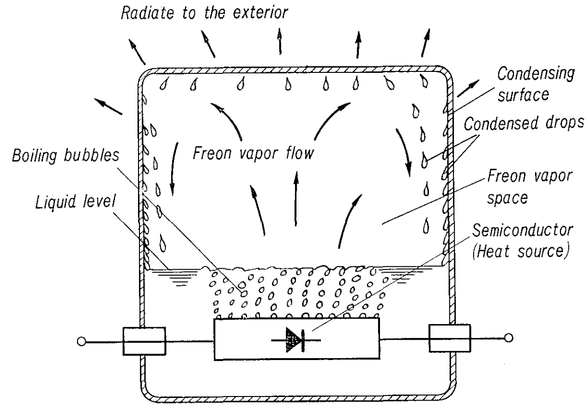

Fig. 3 Principle of cooling system with boiling

III. BASIC FREON TEST DATA

Of all the liquid chemical coolants, Freon has the largest heat transfer coefficient. The results of basic tests concerning heat transfer characteristics, electri-

Table 1 **Characteristics of Water, Transformer Oil, and Chemical Liquids**

	Freon	FC77 Fluorochemical Liquid	Tripen Hexachloro-butadiene	Water	Trans-former oil
Density at 250°C (kg/m³)	1.55	1.78	1.68	0.997	0.86
Boiling Point (°C)	47.6	97.2	215	100	200∼300
Heat of Vaporization at the Boiling Point (kcal/kg)	35	20	—	539	—
Specific Heat at 25°C (kcal/kg·deg)	0.22	0.25	0.19	1.00	0.46
Thermal Conductivity at 25°C (kcal/m·hr·deg)	0.078	0.12	0.10	0.52	0.11
Kinematic Viscosity at 25°C (10^{-6}m²/s)	0.41	0.80	1.68	0.90	14.5
Dielectric Constant at 25°C	2.44	1.86	2.56	—	—
Dielectric Strength at 25°C (kv/mm)	20.0	18.0	20.0	—	12.0
Heat Transfer Coefficient (kcal/m²·hr·deg)	2000∼7000 When boiling	2000∼4000 When boiling	700 When forced convection	4000 When forced convection	350 When forced convection

cal insulation characteristics, resistance of materials to Freon etc. suitable for semiconductor cooling will be described below.

1. Boiling Heat Transfer Characteristics of Freon

The results of tests of the boiling heat transfer of Freon are shown in *Figs. 4* and *5*. *Fig. 4* shows the relation between the temperature difference of the saturation temperature of the coolant and the heat source (deg), and the heat flux density (kcal/m^2·hr). *Fig. 5* gives the relation between the heat flux density and the heat transfer coefficient (kcal/m^2·hr·deg.), which is a clear indication of the cooling power of Freon.

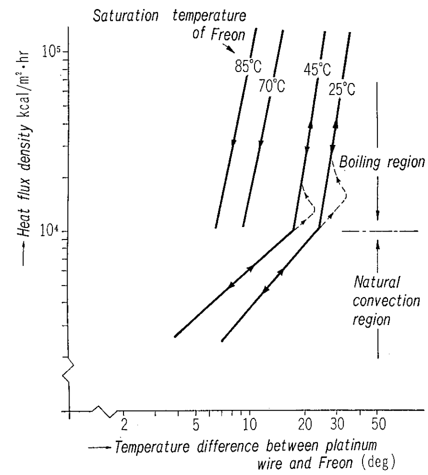

Fig. 4 **Boiling curve for Freon**

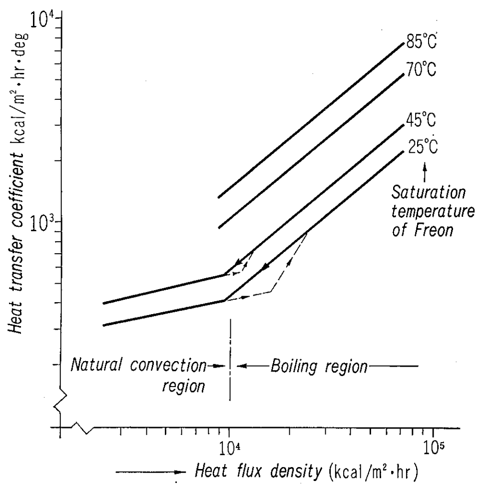

Fig. 5 **Heat transfer coefficients for boiling of Freon**

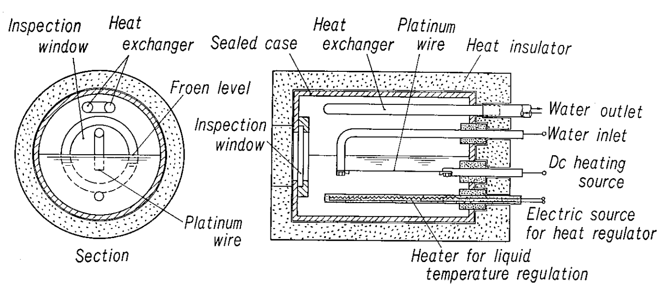

Fig. 6 **Experimental equipment for heat transfer coefficients**

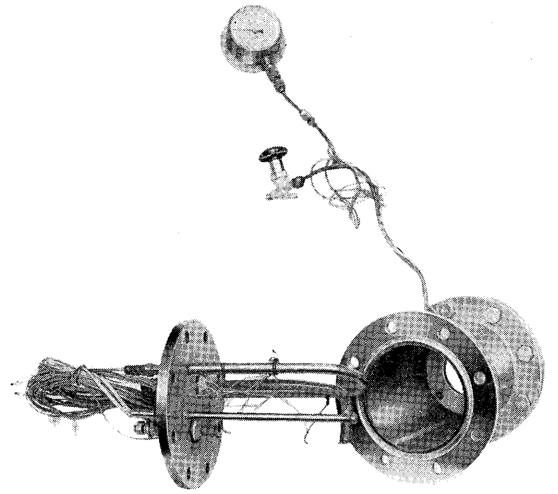

Fig. 7 **Experimental equipment for heat transfer coefficients**

Fig. 6 shows a drawing of the test equipment while *Fig. 7* is an actural photograph. A platinum wire (outer diameter: 0.5 mm) was immersed in Freon liquid and heat was generated from the wire by passing a direct current through it. Boiling then occurred at the surface of the wire. The Freon liquid was placed in the bottom part of a sealed case, almost the same as that described for the boiling type cooling system in section II. In the upper part of this case there was a space for the Freon vapor and a heat exchanger for condensation of this vapor. The heat exchanger was a stainless steel pipe (outer diameter: 13.5 mm) bent in a U-shape and through which cooling water was passed. A heat regulator with a large heat capacity was placed in the Freon liquild so that the heat transfer coefficient could be measured by varying the Freon saturation temperature. The sealed case was covered by a heat insulation material to prevent heat leaks. The temperature of the platinum wire was measured by utilizing the temperature coefficient of the specific resistance of the wire. In addition to the platinum wire, tests were also carried out using a sheathed resistor (outer diameter: 10 mm) and flat surfaced heat source (diameter: 50 mm), but almost the same results were obtained in each case.

As can be seen from the results of these tests, as shown in *Fig. 4*, the curve passes from the natural convection region to the boiling region when the heat flux density was raised to a value of about 10^4 kcal/m^2·hr. Also as the heat flux density increased, the temperature difference became greater, but the slope of the temperature difference increase was very small when compared to that in the natural convection region. This is because boiling becomes stronger as the heat flux density increases and correspondingly heat is absorbed strongly. At this time,

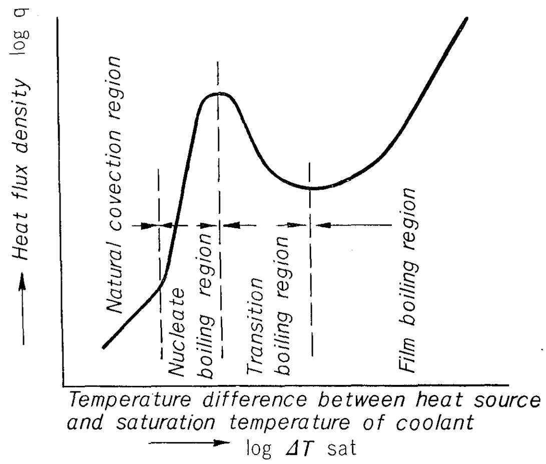

Fig. 8 Typical boiling curve

the relation between the heat flux density q (kcal/m²·hr) and the temperature difference $\varDelta T_{sat}$ (deg.) is as follows.

$$q \propto \varDelta T_{sat}^{m} \quad \cdots\cdots (1)$$

From the test results, the numerical value m is approximately 6. In other words it is possible to remove the heat loss in proportion to approximately the 6th power of the temperature difference $\varDelta T_{sat}$.

Fig. 8[(4)] shows a qualitative representation of the boiling conditions in a so-called boiling curve. The test in *Fig. 4* corresponds to the portion from the natural convection region to the nucleate boiling region in *Fig. 8*. As the heat flux density increases, the curve shifts from the nucleate boiling region to the film boiling region, and the heat transfer decreases. However, this presents no problem since the heat flux density at this time is very high (several hundred thousand kcal/m²·hr).

Fig. 5 shows the heat transfer coefficient for boiling α_b (kcal/m²·hr·deg.) which conforms to the following equation.

$$\alpha_b = q/\varDelta T_{sat} \quad \cdots\cdots (2)$$

The heat transfer coefficient for boiling increases rapidly as the heat flux density increases, and at a heat flux density of about 7×10^4 kcal/m²·hr, the heat transfer coefficient is 7000 kcal/m²·hr·deg. When the heat flux density is held constant, the heat transfer coefficient for boiling reaches a high value with a high Freon saturation pressure (can also be considered as the saturation temperature since a sealed case is used). These characteristics for boiling heat transfer are unique and not found with forced convection for water, transformer oil etc.

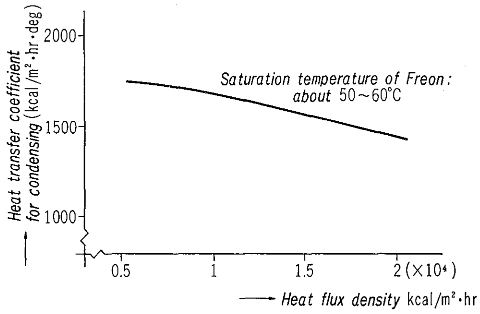

Fig. 9 Heat transfer coefficients for condensing of Freon

2. Heat Transfer Coefficients for Condensing of Freon

This test employed the same equipment as used for the boiling heat transfer with a stainless steel pipe (outer diameter: 13.5 mm) for the condensing of Freon. The results are shown in *Fig. 9*. The heat transfer coefficient for condensing decreases somewhat as the heat flux density increases.

3. Electrical Insulation Characteristics of Freon

Freon has an excellent dielectric strength as shown in *Table 1* and under usual conditions, there is no problem. However, in the boiling-type cooling system, the Freon is usually put in the sealed case when there is almost no air left inside after vacuumization has been carried out. For this reason, boiling and condensation become difficult because of the influence of the partial pressure of the remaining air and the heat transfer characteristics deteriorate. When inserting Freon into the vacuumized case, the pressure inside the case becomes the satura-

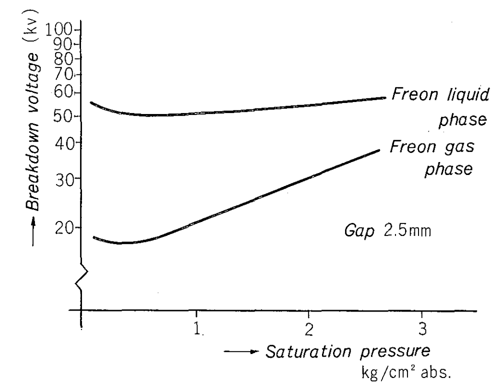

Fig. 10 Breakdown voltage for Freon

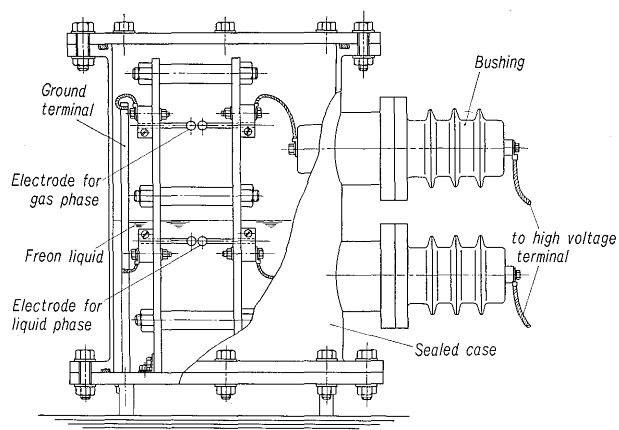

Fig. 11 Experimental equipment for breakdown voltage

tion pressure determined by the temperature of the coolant. For example, at $-10°C$, it is about 0.1 kg/cm^2 abs. With this in mind, the dielectric strength was measured in respect to variations of the saturation pressure as shown in *Fig. 10*. From this it is clear that the decrease in the breakdown voltage at low pressures presents no read difficulty.

As shown in *Fig. 11*, this test was conducted with standard spherical electrodes made of stainless steel and arranged horizontally. Two electrodes were provided ; one for measurements in the liquid phase and one for measurements in the gas phase. The electrode gap was 2.5 mm and, after $2\sim3$ preliminary discharges, measurements were taken while increasing the voltage at a rate of 3000 v/sec.

4. Resistance of the Construction Materials to Freon

Investigation were performed concerning the corrosion of metal and organic materials by the Freon and the deterioration of the Freon caused by these construction materials. The test consisted of placing a test piece in a test tube containing Freon and placing it for about one hour in a thermostatic chamber at 110°C. Test pieces included copper, silver-plated copper, iron, aluminum, nitrile rubber, silicone rubber, teflon (4-fluoride), bakelite, epoxy resin etc. The results showed that except for rubbers no changes were noted in the above materials and all were resistant to Freon. Silicone rubber showed slight swelling but there was no change in the Freon liquid. With nitrile rubber, the swelling was very small but there was some discoloration of the Freon liquid. At present additional tests are being conducted with various types of rubbers including chloroprene rubbers etc. (Since welded construction is used, this point presents no problem).

IV. CONCLUSION

An outline has been given of a new semiconductor cooling method using chemical liquid coolants such as Freon in the boiling state. Since this method gives a much higher heat transfer coefficient than previous cooling methods, the equipment can be very compact, only about 1/2 the size of that used previously. The sealed construction also prevents contamination by dirt or vapors. Since the coolant goes through a boiling/condesation cycle, no special movable parts are required for coolant circulation and maintenance is very easy.

IC (integrated circuits) are used widely for many applications including computers and in the future, LSI (large-scale integrated circuits) will become very common. It is therefore considered that this boiling-type cooling system will come into greater use as partial heat loss increases. Equipment such as transformers and generators is now being made more compact and this cooling technique will also prove very useful as the heat loss density increases. The authors feel that this technique will be used in a wide range of applications in the near future.

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