range 0.1–2 K, and of pure RuO_2 down to 0.05 K. Our data on the thermometers show distinct Schottky-type anomalies at 0.4 K, but no indication of this is present in the specific heat of RuO_2 itself. The origin of this anomaly is not yet clear. The results of the present work show that one should take care in using this type of thermometer in low-temperature microcalorimeters.

Acknowledgements

It is a pleasure to thank D.A. v.d. Straat for his help with the experiments and H.B. Brom for stimulating discussions, G. Frossati of Leiden University for the Dale 700 Ω samples, M.W. Meisel of University of Florida for encouragement in this work and Dale RC-550 samples, and E.H.P. Cordfuncke of the Netherlands Energy Research Foundation for the RuO_2 sample.

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GaAs based varicap as tunable capacitance at millikelvin temperatures

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Received 6 October 1993; revised 30 March 1994

The characteristics of a CXY23/MO67 varicap diode were measured at millikelvin temperatures. The diode can be used as a d.c. voltage tunable capacity element at temperatures even below 20 mK. The heat dissipation caused by the applied d.c. polarization voltage is negligible even at the lowest temperature reached by a dilution refrigerator (13 mK). The d.c. polarizing voltage can be used in the 0–24 V interval at these temperatures.

Keywords: GaAs based varicap; capacitance; ultra-low temperatures

The phenomenon of changing capacity of a p-n diode (varicap) polarized in the reverse direction by a change in applied d.c. voltage is commonly used at room temperature (RT). Typical values of capacitance are several picofarads, with tunability up to a few hundred per cent.

As we plan to perform measurements of tunnelling time from the metastable state of a Josephson junction (JJ)[1] through the variation of the JJ plasma frequency accomplished by tuning a small parallel capacitor of the order of a few picofarads[2], we tested the varicap features at extremely low temperatures (<20 mK), because such temperatures are necessary for the above mentioned experiment with the JJ. At the same time we monitored the influence of the varicap on the cooling system, mainly in terms of heat dissipation during the measurements of capacity and the I–U characteristic.

A GaAs based varicap CXY23/MO67 manufactured by Philips Microwave was chosen, as it is known that the ionization energies for donor and acceptor ions are lower in GaAs in comparison with other common semiconductors (Si, Ge). The experiment was carried out in a dipstick 'Minidil' dilution refrigerator (10 mK model) supplied by TBT, France. The temperature in the mixing chamber was measured by means of a calibrated Ru_2O resistor and an a.c. resistance bridge ORPX-2 (Barras Provence, France). The body of the varicap (∅1×2 mm) was glued directly on the mixing chamber wall using GE-7031 varnish together with a 0.05 mm isolation Mylar foil, and the varicap connections were thermally grounded in the same way.

As for the capacity measurements, the varicap was first measured at room temperature in a resonant circuit using a high frequency probing signal (22 MHz)

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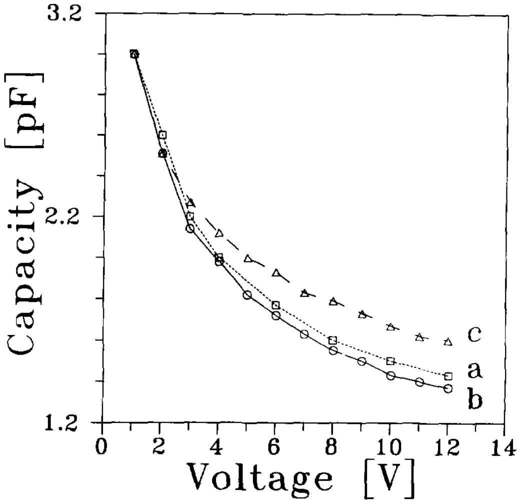

Figure 1 CXY23/MO67 varicap capacity as a function of applied d.c. voltage. Curve a, measured at room temperature in resonant circuit using 22 MHz probing signal and Q meter; b, measured at room temperature with impedance bridge GR 1650-A using 1 kHz probing signal; c, same as b at $T \leq 20$ mK

and a Q meter. The measured C–U characteristics are shown in *Figure 1*, curve a. Because the design of the Minidil refrigerator did not allow us to use the same approach, in this case we used an impedance bridge (type 1650-A, General Radio Company, Massachusetts, USA). The bridge uses a 1 kHz probing voltage $U(t) = 1.3 \times \sin(2000\pi t)$ V and a d.c. bias voltage can be directly connected to it. Departure of the bridge meter from the balanced 'zero' position was used to monitor the change of varicap capacity, and precise calibration by 0.1 pF capacitors was performed so as to be able to measure the changes in varicap capacity with a resolution better than 0.1 pF. A sine wave generator and oscilloscope were used to test the varicap in terms of its $I–U$ characteristic with an external resistor R_{ex} = 1 (10) MΩ to minimize heat dissipation at the varicap p-n junction.

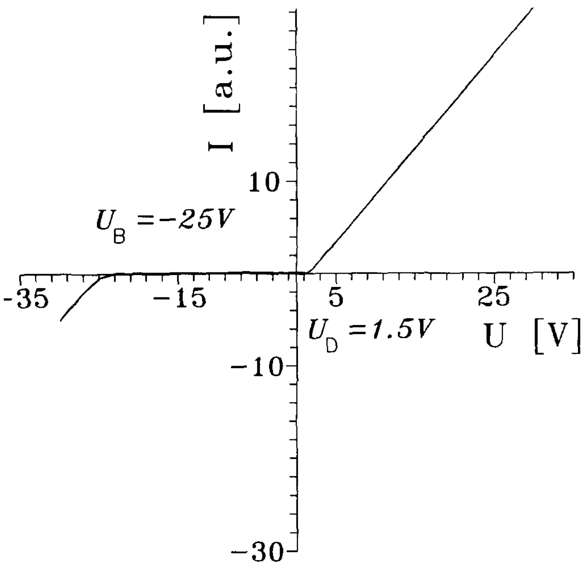

Figure 2 External resistor limited $I–U$ characteristics of the CXY23/MO67 varicap measured at $T = 50$ mK (at mixing chamber of refrigerator). U_B and U_D are defined in the text

Two temperature runs were performed (in which the lowest temperatures $T = 23$ and 13 mK were reached, respectively) and the varicap characteristics tested. The results are shown in *Figures 1* and *2*. It was found that the capacity of the varicap CXY23/MO67 can be tuned even at temperatures below 20 mK (*Figure 1*, curve c), and only slightly reduced performance is obtained in comparison with that at room temperature (*Figure 1*, curve b). At $U = -4$ V the capacitance per unit area $C_u = 0.14 \mathrm{fF} \mu\mathrm{m}^{-2}$ was derived**. A small degree of overheating (from 13 to 18 mK) was observed in the second run during the capacity measurements due to heat dissipation at the p-n junction resulting from the 1 kHz probing voltage. When only d.c. polarizing voltage was applied, even at 13 mK no changes in temperature were observed, i.e. the heat dissipation given by the minority carrier current through the p-n junction was negligible.

On the contrary, the heat dissipation during the $I–U$ characteristic measurements did not allow us to cool the mixing chamber to temperatures lower than $T = 50$ and 30 mK for $R_{ex} = 1$ and 10 MΩ, respectively. It is difficult to estimate the true temperature of the p-n junction itself during the $I–U$ measurements, but it was probably ≈100 mK or even higher. An example of an external resistor limited $I–U$ characteristic is shown in *Figure 2*. It is obvious that the varicap behaves as a diode, and the values of the breakdown voltage U_B and the diffusion voltage U_D are given for several temperatures in *Table 1* (for temperatures above 4.2 K the figures were obained from other measurements).

The decrease in U_B when the temperature is lowered is due to increased efficiency of impact ionization in the p and n bulk of the varicap system. It is interesting to note that U_B decreases down to the milikelvin range of temperature, so that this characteristic might be used for temperature monitoring over a very wide temperature region, under the assumption of sufficiently low heat dissipation in the varicap. The increasing value of U_D is connected with the temperature dependence of the Fermi level within the gap, and possibly also with the increase of serial resistance of the contacts and the increase of the GaAs gap with decreasing temperature.

Table 1 Temperature dependence of breakdown voltage U_B and diffusion voltage U_D according to the $I–U$ characteristics of the CXY23/MO67 varicap

T(K)	U_B(V)	U_D(V)
295	44	0.8
100	34	—
18	30	1.5
0.05	25	1.5

**The geometry of the varicap p-n junction, and the kind of donor and acceptor ions and their concentration were obtained from Philips Microwave

The diffusion voltage at the p-n junction is given by the equation[3]

$$U_{\mathrm{D}} = \frac{kT}{e} \times (\psi_1 - \psi_2) \qquad (1)$$

where $\Psi_{1,2}$ are the reduced potentials in the n and p layer of the p junction, which can be written in the form

$$\Psi_1 = \frac{E_{\mathrm{Fn}} - E_{\mathrm{i}}}{kT}, \quad \Omega_2 = \frac{E_{\mathrm{Fp}} - E_{\mathrm{i}}}{kT} \qquad (2)$$

where E_{i} represents the intrinsic Fermi level and E_{Fn}, E_{Fp} are the electron and hole Fermi levels, respectively. For temperatures near to 0 K the E_{Fp}, E_{Fn} Fermi levels are in between the acceptor energy level and the top of valence band E_{V} in the p region and in between the donor energy level and the bottom of conduction band E_{C} in the n region of the p-n junction. For the type CXY23/MO67 varicap with capacitance $C(-4\,\mathrm{V}) = 2.0$–$2.1\,\mathrm{pF}$ and breakdown voltage $U_{\mathrm{B}}(295\,\mathrm{K}) = 44\,\mathrm{V}$ (our measured values), the n layer of the p-n junction was created by Zn doping with a $1.5 \times 10^{20}\,\mathrm{cm}^{-3}$ concentration and the layer was created by Si doping with a $1.1 \times 10^{16}\,\mathrm{cm}^{-3}$ concentration*. The energy level of the Zn acceptor ions is situated 4 meV above E_{v} and that of the Si donor ions 2 meV below E_{c}. The energy gap of GaAs at 0 K is $E_{\mathrm{g}} = 1.519\,\mathrm{eV}$.

Using these characteristics and Equations (1) and (2) the diffusion voltage $U_{\mathrm{D}} = 1.506\,\mathrm{V}$ was calculated; this value is practically independent of the donor and acceptor concentration at milikelvin temperatures. For increasing temperatures the E_{Fp} and E_{Fn} Fermi levels are shifted towards the centre of the band gap, which leads to a decrease in U_{D}, with a known value of $U_{\mathrm{D}} = 0.8\,\mathrm{V}$ at room temperature. Both calculated values are in very good agreement with our measured values in *Table 1*.

There are basically two models[4] explaining the conductivity mechanism in doped semiconductors at extremely low temperatures when kT is too small to ensure a sufficient concentration of electrons and holes in the conduction and valence bands, respectively. For low concentrations of acceptor (donor) ions the 'hopping' is considered to occur between their energy levels (possibly the case for the n-region of the varicap), while for rather high concentrations the creation of an impurity energy level band is proposed, to allow for carrier motion under an electric field (the p-region of the varicap).

Acknowledgements

The partial financial support of the Center for Technological Development (CESVIT) of Provincia di Firenze is gratefully acknowledged. One of the authors (MN) undertook this work with the support of the ICTP Programme for Training and Research in Italian Laboratories, ICTP, Trieste. The authors are grateful to J. Ovey from Philips Microwave for providing the physical characteristics of the varicap.

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See previous footnote